Report No. CG-D-21-96

THE LEEWAY OF CUBAN REFUGEE RAFTS AND A COMMERCIAL FISHING VESSEL

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Interim Report
May 1996

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Prepared for:

U.S. Department of Transportation
United States Coast Guard
Office of Research and Development
Washington, DC 20593-0001

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Technical Report Documentation Page

1. Report No. CG-D-21-96	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle The Leeway of Cuban Refugee Rafts and a Commercial Fishing Vessel		5. Report Date May 1996
		6. Performing Organization Code
7. Author(s) Arthur A. Allen		8. Performing Organization Report No. R&DC 12/96
9. Performing Organization Name and Address U.S. Coast Guard Research and Development Center 1082 Shennecossett Road Groton, Connecticut 06340-6096		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
		13. Type of Report and Period Covered Interim Report
12. Sponsoring Agency Name and Address Department of Transportation U.S. Coast Guard Office of Research and Development Washington, D.C. 20593-0001		14. Sponsoring Agency Code Commandant (G-NRS) USCG Headquarters Washington, D.C. 20593-0001

15. Supplementary Notes

This report is the eighteenth in a series that documents the Improvement of Search and Rescue Capabilities (ISARC) Project at the USCG R & D Center. The R&DC technical point of contact is Arthur Allen, 860-441-2747.

16. Abstract

A field test of the leeway of two search and rescue (SAR) craft was conducted during the period 25 October to 3 November 1994 by the U.S. Coast Guard Research and Development Center. The experiment was conducted off the east coast of Florida. The SAR craft included a Cuban refugee raft with and without a sail, and a 15 meter commercial fishing vessel with a rear-reel for net fishing.

This report summarizes statistical analysis of these data. A technique is introduced for incorporating the uncertainty of the measured observations of leeway from these experiments into the uncertainty of the prediction of the leeway component of a survivor craft. The Cuban refugee raft without sail had leeway speeds greater than 1.5 percent of the wind speed adjusted to 10m height and was within 30 degrees of the downwind direction. The Cuban refugee raft with sail had leeway speeds less than 8.0 percent of 10m wind speed, and was within 45 degrees of the downwind direction. The medium displacement fishing vessel leeway was 4.0 percent of the 10m wind speed and was 30 $\pm$ 15 degrees either left or right of the downwind direction.

17. Key Words	18. Distribution Statement
search and rescue leeway Cuban refugee rafts leeway covariance medium displacement vessel	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. SECURITY CLASSIF. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

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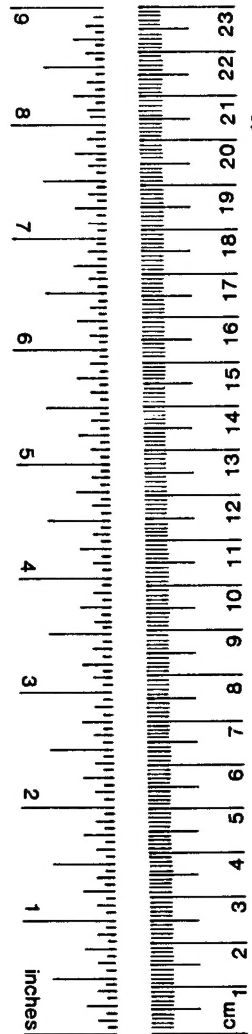
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

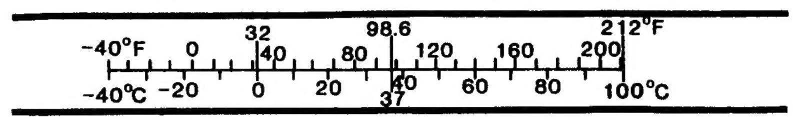
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ACKNOWLEDGEMENTS

I thank Dr. Don Olson and Dr. Gary Hitchcock of the University of Miami for the construction and loan of the Cuban Refugee Raft.

The professional efforts of the Captain and crew of F/V LITTLE GLEN, Glen Black and "Big" Mike were greatly appreciated.

Special thanks to Gary Reas and Chris Oates for the technical support and calibration of the instruments and to Dave Brennan for converting the Smith(1981) wind adjustment program.

The comments of Dr. Don Murphy, Louis Nash, Vonnie Summers and Renee Mercaldo-Allen were appreciated and helped me improve this report.

I thank LT Chris Rodriquez for guiding me through the statistical portion of the analysis.

Finally, the assistance of Quincy Robe is gratefully acknowledged.

LIST OF ACRONYMS AND ABBREVIATIONS

A/D	Analog to Digital
Abs	Absolute Value
ASCII	American Standard Code for Information Interchange
C-MAN	Coastal Marine Automated Network
CANSARP	CANadian Search And Rescue Prediction program
CASP	Computer Assisted Search Planning program
cm/s	centimeters per second
CODE	Coastal Ocean Dynamics Experiment
CWL	Crosswind Component of the Leeway Vector (cm/s)
d.f.	Degrees of Freedom
dia	Diameter
DWL	Downwind Component of the Leeway Vector (cm/s)
EMCM	Electromagnetic Current Meter
F/V	Fishing Vessel
FAU	Florida Atlantic University
ft	Feet
GPS	(NavStar) Global Positioning System
HDOP	Horizontal Dilution of Precision
Hgt	Height
HH	Hour format (00-23)
Hz	Hertz (1/second)
km	Kilometers
kts	Knots (international)
L	Leeway Vector (cm/s)
LKP	Last Known Position
m	Meters
m/s	Meters per second
MHz	MegaHertz (1/1000 seconds)
min	Minute
MM	Minute format (00-59)
MRS	(Motorola) Mini-Ranger microwave positioning System
MSE	Mean Square Error
MTS	(Motorola) Microwave Tracking System
n	Number of points used in a regression
Neg.	Negative
PIW	Person-In-the-Water
Pos.	Positive
R&DC	Research and Development Center
r^2	Coefficient of determination
RDF	Radio Direction Finder
RWD	Relative Wind Direction
SAR	Search and Rescue
SLDMB	Self-Locating Datum Marker Buoy
SS	Second format (00-59)
$S_{s/x}$	Standard Error of the Estimate
std. dev.	Standard Deviation
UHF	Ultra High Frequency

LIST OF ACRONYMS AND ABBREVIATIONS (Continued)

USCG	United States Coast Guard
USCGC	United States Coast Guard Cutter
UTC	Universal Coordinate Time
Var	Variable
w/	With
w/o	Without
W_{10m}	Wind Speed Vector Adjusted to 10 meter height
YYMMDD	Year Month Day format (e.g. 950625)

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EXECUTIVE SUMMARY

INTRODUCTION

A field test of the leeway of two search and rescue (SAR) craft was conducted in the fall of 1994 by the U.S. Coast Guard Research and Development Center (R&DC). The experiment was conducted off the east coast of Florida. The SAR craft included a Cuban Refugee Raft with and without a sail, and a 15 meter commercial fishing vessel with a rear-reel for net fishing.

This report summarizes statistical analysis of these data. A technique is introduced for incorporating the uncertainty of the measured observations of leeway from these experiments into the uncertainty of the prediction of the leeway component of a survivor craft.

Leeway is defined in the National SAR Manual as "movement of a craft through the water caused by wind acting on the exposed surface of the craft." Fitzgerald et al. (1993) proposed a revised leeway definition of:

> "Leeway is the velocity vector of a SAR object relative to the downwind direction of the search object as it moves relative to the surface current measured between 0.3m and 1.0m depth caused by winds (adjusted to a reference height of 10m) and waves."

Results of this report are presented using this revised definition of leeway. The wind vectors adjusted to the 10 meter reference height are referred to in this report as $\mathbf{W_{10m}}$.

The direct method, first used by Fitzgerald et al. (1993), was used to measure leeway in this experiment. An InterOcean S4® electromagnetic current meter (EMCM) was tethered to the SAR object to measure velocity relative to the water. Winds, surface currents, and total displacement of the SAR craft were also measured.

RESULTS

This study was conducted on the high and low drift version of a Cuban Refugee Raft, and a medium displacement fishing vessel.

A simple model that provides the maximum and minimum leeway speed is recommended for implementation during manual search planning for the Cuban Refugee Raft. The constrained model is recommended for the fishing vessel. These models are valid when the winds are less

than 10m/s (20 knots). Table ES-1 summarizes the manual leeway equations for Cuban Refugee Rafts and a 15 meter commercial fishing vessel set up for net fishing. The Cuban Refugee Rafts exhibited a large variation in leeway angles, therefore, the two large ranges of angles are presented for each craft. Cuban Refugee Rafts without sails can be expected to drift within 30° of the downwind direction, whereas Cuban Refugee Rafts with sails can sail off the downwind direction by as much as 45°. The fishing vessel leeway angle was either left or right of the downwind direction by 30° $\pm$ 15° standard deviation.

Table ES-1
Summary of Manual Leeway Equations

(**L** = Leeway speed (cm/s))
(W_{10m} = 10m Wind Speed (m/s))

CLASS	CRAFT	EQUATION	Leeway Angle	W_{10m} (m/s)
Refugee Rafts	w/o Sail	$L = 1.5\% \ W_{10m}$	0° $\pm$30°	2 - 7
	w/Sail	$L = 8.0\% \ W_{10m}$	0° $\pm$45°	2 - 7
Medium Displacement fishing vessels	15m Rear-reel Net fishing	$L = 4.0\% \ W_{10m}$	+30° $\pm$15° and -30° $\pm$15°	1 - 9

The statistical models of the leeway components and their prediction limits are recommended for implementation in numerical search planning models. Both plus and minus crosswind equations should be vector added to the downwind equation to produce the leeway prediction. An example of using the prediction limits of the leeway components to estimate the distribution of the predicted leeway vectors is introduced in Chapter 5. The implementation of leeway prediction limits into numerical search planning models is the topic of the forthcoming R&D Center project, Leeway Covariance.

The linear regression models are recommended when the 10 meter wind speed is less than 10m/s (20 knots). The equations for the mean, upper and lower 95% prediction limits for Cuban Refugee raft's leeway components on the 10 meter wind speed are presented in Table ES-2.

Table ES-2
Summary of Cuban Refugee Raft Leeway Equations

(**DWL** = Downwind Component of Leeway(cm/s))
(**CWL** = Crosswind Component of Leeway(cm/s))
(W_{10m} = 10m Wind Speed (m/s))
(c_1, c_2, and c_3 are coefficients from Eq. 3-10)

Cuban Refugee Rafts without Sails

Mean **DWL** = 1.56% W_{10m} + 8.3 cm/s
Mean **+CWL** = 0.078% W_{10m} + 2.7 cm/s
Mean **-CWL** = -0.078% W_{10m} - 2.7 cm/s

Dependent Variable	Upper Limits			Lower Limits		
	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3
DWL	0.0078	1.4909	11.5154	-0.0078	1.6328	-5.0751
+CWL	0.0077	0.0078	5.8939	-0.0077	0.1484	-0.4897
-CWL	0.0077	-0.1484	0.4897	-0.0077	-0.0078	-5.8939

Cuban Refugee Rafts with Sails

Mean **DWL** = 6.43% W_{10m} - 3.47 cm/s
Mean **+CWL** = 5.19% W_{10m} - 16.2 cm/s
Mean **-CWL** = -5.19% W_{10m} + 16.2 cm/s

Dependent Variable	Upper Limits			Lower Limits		
	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3
DWL	0.0496	5.910	5.2184	-0.0496	6.9572	-12.149
+CWL	0.0889	4.2480	-0.6341	-0.0889	6.1255	-31.770
-CWL	0.0889	-6.1255	31.770	-0.0889	-4.2480	0.6341

For the 15m commercial fishing vessel equipped with a rear-reel for net fishing, the linear regression models of the downwind and crosswind components of leeway on wind speed are recommended for use in numerical models. The mean, upper and lower 95% prediction limits equations for 15m commercial fishing vessel's leeway components on the 10 meter wind speed are presented in Table ES-3.

Table ES-3

Summary of
15m Commercial Fishing Vessel with Rear-reel for Net Fishing - Leeway Equations

(**DWL** = Downwind Component of Leeway(cm/s))
(**CWL** = Crosswind Component of Leeway(cm/s))
($\mathbf{W_{10m}}$ = 10m Wind Speed (m/s))
(c_1, c_2, and c_3 are coefficients from Eq. 3-10)

15m Commercial Fishing Vessel with Rear-reel for Net Fishing						
Mean **DWL** = 3.72% $\mathbf{W_{10m}}$ - 0.87 cm/s Mean **+CWL** = 1.41% $\mathbf{W_{10m}}$ + 2.00 cm/s Mean **-CWL** = -1.41% $\mathbf{W_{10m}}$ - 2.00 cm/s						
Dependent Variable	Upper Limits			Lower Limits		
	$c_1(\mathbf{W_{10m}})^2$	$c_2(\mathbf{W_{10m}})$	c_3	$c_1(\mathbf{W_{10m}})^2$	$c_2(\mathbf{W_{10m}})$	c_3
DWL	0.0070	5.8787	3.6507	-0.0070	3.3737	-7.6245
+CWL	0.0070	1.3380	8.7976	-0.0070	1.4721	-4.8039
-CWL	0.0070	-1.4721	4.8039	-0.0070	-1.3380	-8.7976

CHAPTER 1

INTRODUCTION

1.1 SCOPE

The 1994 Leeway Experiment was a joint experiment by the U.S. Coast Guard Research and Development Center (R&DC), the University of Miami, and the South Florida Oil Spill Research Center. The experiment was conducted in the Atlantic Ocean off Fort Pierce, Florida from 24 October to 4 November 1994. The direct method of measuring leeway was used during this experiment. The objective of this experiment was to determine the leeway rates and divergences used in drift prediction for search and rescue (SAR).

The flight of refugees from Cuba reached a peak in the summer of 1994, when many hundreds of Cubans were leaving by boats and make-shift rafts each day. Before this mass exodus, there were several hundred attempts each year by Cubans to reach the U.S. mainland by boat or raft. Prediction of the movement and distribution of rafts is of interest to the U.S. Coast Guard, University of Miami and the Cuban-American group "Brother to the Rescue." The Coast Guard uses their Computer Assisted Search Planning (CASP) numerical search model for predicting the drift of individual SAR targets, such as Cuban Refugee Rafts. Scientists at the University of Miami ran a numerical model for the Florida Straits area that includes wind and currents. The University of Miami model was used to predict the distribution of Cuban refugee rafts after several days of drift away from the starting point near Havana on the north shore of Cuba. "Brothers to Rescue" and the U.S. Coast Guard used the University of Miami predicted distributions to help plan surveillance flights to search for Cuban Refugee Rafters. Neither Coast Guard's CASP model nor the University of Miami model used measured leeway values for Cuban Refugee Rafts. After inspecting about fifty actual Cuban Refugee Rafts collected by the "Brothers to the Rescue," a prototypical Cuban Refugee Raft was constructed for a leeway study.

The results of this work are expected to be used to update SAR planning guidance material provided in the National Search and Rescue Manual (1991) and in CASP computer models. A full scale model of a typical Cuban refugee raft was constructed. The model was tested for both low and high leeway configurations to provide the range of leeway rates expected for this type of craft for use as inputs into CASP and the University of Miami model. The support vessel for this work was the Fishing Vessel LITTLE GLEN, a 15 meter rear-reel commercial fishing vessel typical to the Florida area. The leeway of the F/V LITTLE GLEN was also measured. The F/V LITTLE

GLEN was an example of the leeway class of medium displacement fishing vessels from the National Search and Rescue Manual (1991).

Chapter 1 is a review of the methods of previous leeway experiments for measuring leeway, currents, and winds. The methods and leeway craft used during this experiment are described in Chapter 2. Summary of data reduction and a review of the statistical methods used are presented in Chapter 3. Results of the statistical models for the leeway craft are presented in Chapter 4. A technique is introduced in Chapter 5 for incorporating the uncertainty of the measured leeway from these experiments into the uncertainty of the prediction of the leeway components of a survivor craft. Chapter 6 contains recommendations, conclusions and suggestions for future work in this area.

This report presents the results of the R&DC's analysis of the leeway data. R&DC participated in the experiment under element 1012.3.7, Leeway of small SAR objects, in the Improvements to Search and Rescue Capabilities (ISARC) project. University of Miami's participation was funded under the South Florida Oil Spill Research Center funding.

1.2 BACKGROUND

1.2.1 Leeway in Search and Rescue

A key element of a successful search is the accurate prediction of the total displacement of a SAR target from its estimated Last Known Position (LKP). For a search object located on the surface of the water, the total displacement is the vector addition of the sea surface currents and leeway.

For the search planner using manual methods, the components of leeway include leeway speed and leeway angle. Leeway speed is the speed at which the wind will push an object through the water. Leeway angle is the angle off the downwind direction which the object sailed. Expressing leeway in terms of its downwind and crosswind components instead of leeway speed and leeway angle, has advantages for interpretation of behavior and for ease of incorporation into the numerical models.

Leeway as defined by the National SAR Manual is "that movement of a craft through the water, caused by the wind acting on the exposed surface of the craft." This definition of leeway is physically correct, but has two major operational shortcomings. Objects on the surface of the ocean are at the interface of two boundary layers where there is high vertical shear in the velocity profiles of wind and sea currents. Fitzgerald et al. (1993) proposed a revised leeway definition:

> "Leeway is the velocity vector of the SAR object relative to the downwind direction at the search object as it moves relative to the surface current as measured between 0.3m and 1.0m depth caused by winds (adjusted to a reference height of 10m) and waves".

This definition standardizes the reference levels for the measurement of the leeway of SAR objects. Both of these levels are readily available to the operational SAR planner. Most "sea level" wind products are adjusted to the 10 meter height. The new Self-Locating Datum Marker Buoys (SLDMBs) are designed with drag elements between 0.3 m and 1.0 m depth.

1.2.2 Previous Leeway Investigations

Leeway field studies previous to Fitzgerald et al. (1993) estimate leeway by subtracting the sea current vector from the total displacement vector to estimate the leeway vector. These investigations are summarized by Nash and Willcox, 1991. Table 1-1 summarizes the methods of measuring sea currents and winds used in the previous leeway investigations.

The leeway studies prior to Fitzgerald et al. (1993) have several shortcomings in the data collection. The methods of measuring ocean currents used by the studies previous to Fitzgerald et al. (1993) contain systematic slippage errors. For the dye patch method, there is uncertainty in the depth of dye patch as measured by aerial photography. Navigational errors in determining the location of drifters and leeway targets caused errors of the leeway estimates. Drifters used to measure surface currents were not located with the leeway target.

Winds were determined by reading the ship anemometer or by measurements at the leeway target. Ship's winds tended to overestimate the wind speed (reading bias, plus flow distortion over ship, added to unreported anemometer heights). Wind data from anemometers at 2 meter height aboard leeway targets required adjustment for motion of target and then adjustment to the standard 10 meter reference level using a boundary layer model for winds.

The error of the leeway estimates for a SAR object included all the errors in the associated sea current measurements, the wind measurement, and the navigational errors used for determining the velocity of SAR objects. The surface currents at the time and position of the SAR object were interpolated or extrapolated from the sea current measurements. Maintenance of an array of sea surface current measuring instruments, relative to drifting leeway target, was a major logistical problem, leading to short or discontinuous data sets.

Table 1-1
Previous Leeway Studies'
Methods of Measuring Sea Currents and Wind

STUDY	SEA CURRENTS	WINDS	NAVIGATION
Pingree (1944)	upper 15 ft	at 10 ft	not reported
Chapline (1960)	15x300 ft drift net	Buoy Tender	Radar & visual Bearing & ranges
Hufford and Broida (1974)	Dye Patch aerial Photographed every 5 min.	Cup-anemometer at 2 m, reading at 5 min intervals	Scaling of aerial photographs by landmarks and altitude
Morgan et al. (1977)	28 ft. dia parachute drogue, tracked by ship, 20 min sampling	USCGC(s) EVERGREEN COURAGEOUS LAUREL ROCKAWAY	Range (radar) Bearing (visual or radar)
Scobie and Thompson (1979)	15 ft buoy w/ 10x10 ft window shade drogue tracked by ship	USCGC EVERGREEN hourly readings	Visual & radar bearing and ranges from ship
Osmer et al. (1982)	Buoy w/ window shade drogue tracked by ship, Expendable surface current probes	USCGC EVERGREEN 15 min readings	MRS for range visual bearing using ship's pelorouses, ship position Loran-A or C
Nash and Willcox (1985) and (1991)	Surface Drifters tracked by MTS at 2 min intervals	R.M. Young anemometer 6ft 3 sec averages every 30 or 40 seconds	Microwave Tracking System (MTS)
Su(in press)	Surface drifters of FAU design	C-MAN station anemometer 20 ft, hourly	Triangulation from shore using transits
Fitzgerald et al. (1993) and (1994)	Leeway measured directly using EMCMs at 0.7 m depth 10 min. averages	R.M. Young anemometer 2m or 3m, 10 minute averages, adjusted to 10m using Smith (1988)	(1993) Loran-C (1994) GPS

Fitzgerald et al. (1993) conducted an experiment off Newfoundland during the summer of 1992 to compare the indirect method with the direct method of determining leeway. The direct method eliminates many of the errors associated with previous techniques by directly measuring the leeway of the SAR object using an attached current meter. A wind monitoring system was placed aboard the SAR object along with positioning system and a locating beacon. Long continuous records of leeway were obtained even in high wind conditions. The errors of measuring, interpolating or extrapolating sea currents to the location of drifting leeway target were eliminated. Remaining errors were random instrument errors and systematic errors associated with interactions between the measuring instruments and the SAR object. With the direct method, the SAR object was modified by the addition of a wind monitor and a tether current meter. The wind monitor had a minimal effect on the drift of medium size SAR targets. The SAR object possibly distorts or deflects the wind field locally causing a systematic error in both speed and direction at location of the anemometer. The tethered current meter acted as a drogue and may have affected the crosswind component of leeway by reducing jibing.

CHAPTER 2

THE EXPERIMENT

2.1 DESIGN AND CONDUCT

The field experiment was conducted off Fort Pierce, FL, between 25 October and 3 November 1994. Leeway was directly measured using a tethered current meter. All leeway drift runs were conducted near a moored meteorological buoy which measured winds and wave height. Additional wind measurements were collected aboard the leeway targets. Two types of surface current measurements were made. A current meter was attached to the float line of the meteorological buoy at the beginning of the third sampling day to provide Eulerian surface current information. Surface drifters were also released and recovered in the experiment area to provide Lagrangian estimates of surface currents. GPS data loggers were used to measure total displacement of the leeway craft. A transmitting beacon was aboard the Cuban Refugee Raft to aid in its recovery.

2.1.1 Measurement of Leeway

The direct method of Fitzgerald et al. (1993) was used to measure leeway in this experiment. An InterOcean S4® electromagnetic current meter (EMCM) was tethered to the SAR object to measure velocity relative to the water. The S4® EMCMs were suspended with an aluminum frame at 0.75 meters depth. The frame was attached to a float sized to match the drift of the leeway craft. The frame with S4® EMCM was attached by a 15 meter line to the pivot point of the leeway craft.

The InterOcean S4® EMCMs sampled at 2 Hz, and were vector averaged over 10 minute periods. An internal flux-gate compass converted the two orthogonal components of velocity to magnetic north and east coordinates. The raw directions of currents from the S4® EMCM were adjusted for the magnetic variation (+4.69 degrees) and then rotated 180 degrees. Two tilt sensors in the S4® EMCM were used to apply, at 2 Hz, the cosine correction for the tilt angle to the current speed. Temperature at 0.75 meter depth was also sampled every 10 minutes. The S4® EMCMs were calibrated yearly by InterOceans.

2.1.2 Measurement of Wind

The wind was measured using R.M. Young anemometers aboard the leeway targets and with a Coastal Climate MiniMet® buoy. The anemometers were sampled at 1 Hz and vector averaged over 10 minute periods. The anemometers aboard the leeway targets were connected

to Coastal Climate's Weatherpak® system. The two Weatherpaks® stored and transmitted via UHF the following wind data every 10 minutes:

YYMMDD HH:MM:SS of start of sampling period
10 minute vector averaged wind speed
10 minute scalar averaged wind speed
10 minute vector averaged wind direction
10 minute vector averaged of vane bearing
Std. deviation of vane bearing
Max. 5 second wind gust
Time of wind gust
Std. deviation of wind speed
Instantaneous Air Temperature
Weatherpak® internal temperature
Battery voltage

A Coastal Climate MiniMet® meteorological buoy was moored in the center of the experiment area. The wind measurements from the MiniMet® buoy were used to calibrate the wind measurement from the leeway targets. The MiniMet® buoy R.M. Young anemometer was mounted at a 3 meter height. The MiniMet® buoy sampled 1 Hz for 10 minutes at 0 to 10 minutes and 30 to 40 minutes past the hour. Wave height sampling was conducted at 10-30 minutes past each hour. The MiniMet® Buoy sampled the following every half hour:

YY:MM::DD HH:MM time at start of sampling
10 minute vector average of wind speed
10 minute vector average of wind direction (magnetic from)
10 minute scalar average wind speed
Last instantaneous compass heading
Last instantaneous vane bearing
5 second wind maximum (gust)
Water temperature at 2 meter depth
Air temperature at 3 meter height
Latitude from the GPS receiver
Barometric pressure at 3 meter height

The MiniMet® buoy wave data included significant wave height and wave energy spectrum.

The R.M. Young anemometers were calibrated prior to the field testing for both speed and relative bearing. The anemometers were then paired with a Weatherpak® or MiniMet® buoy. A second calibration was conducted of the anemometer - A/D converter system. The compasses in the Weatherpaks® and the MiniMet® were also calibrated to determine deviations. The MiniMet® compass deviation corrections were applied at the 1 Hz sampling interval. Both the MiniMet® and WeatherPak® relative heading corrections were applied

in post processing to the 10 minute samples. Compass deviation corrections for the WeatherPak® compass were applied in post processing at the 10 minute sample interval. The error of wind direction from the MiniMet® wind monitoring system was estimated to be ± 2°. The error of wind direction from the WeatherPak® wind monitoring system was estimated to be ± 10° before adjustment to MiniMet® winds and ± 4° after adjustment.

2.1.3 Measurement of Drift

On board each leeway craft was a six channel Magellan Global Positioning System (GPS) receiver and data logger. The GPS position and time were stored at 5 minute intervals by a Tattletale® data logger. The GPS receiver, data logger and batteries were housed in a waterproof case. The GPS antenna was mounted on board the leeway craft and connected through a watertight bulk-head connection in the waterproof case to the GPS receiver.

GPS positions during the experiment period had an accuracy of better than 100 meters 97 percent of the time.

2.1.4 Measurement of Sea Surface Currents

Two methods of measuring the sea surface currents were used. Eurlian currents were measured by a S4® EMCM attached to MiniMet's® surface float line, at 0.75 meter depth. Lagrangian currents were measured by the deployment and recovery of several surface drifters during each leeway deployment.

At the beginning of the third sampling day an S4® EMCM was attached to the float line of the MiniMet® buoy. This position in the float line isolated the S4® EMCM from the mooring line strumming interference and influence of the MiniMet® buoy hull. The float line follows the surface waves that have periods greater than 4 seconds. The S4® EMCM sampled at 2 Hz, and was averaged over 10 minute periods continuously. A cosine correction for tilt was applied to the horizontal currents using the two vertical tilt sensors. Sea surface temperature at 0.75 meter depth was sampled every 10 minutes. The horizontal currents were corrected for the horizontal motion of the MiniMet® about its anchor.

Surface drifters were deployed and recovered during each leeway run for an associated experiment. These surface drifters, (Figure 2-1), were a 7/10th scaled version of the Coastal Ocean Dynamics Experiment (CODE) drifter developed by Davis (1985). The 7/10th CODE drifters had drag vanes that spanned the depth range 0.3 to 1.0 meters. The drifters were positioned twice, at deployment and

at recovery, by the using GPS positions from the data logger on board the work vessel. The purpose of the drifter experiment was to investigate slippage errors of the $7/10^{th}$ CODE drifter with four different float shapes. The drift error for these drifters was assumed to be the GPS positional error.

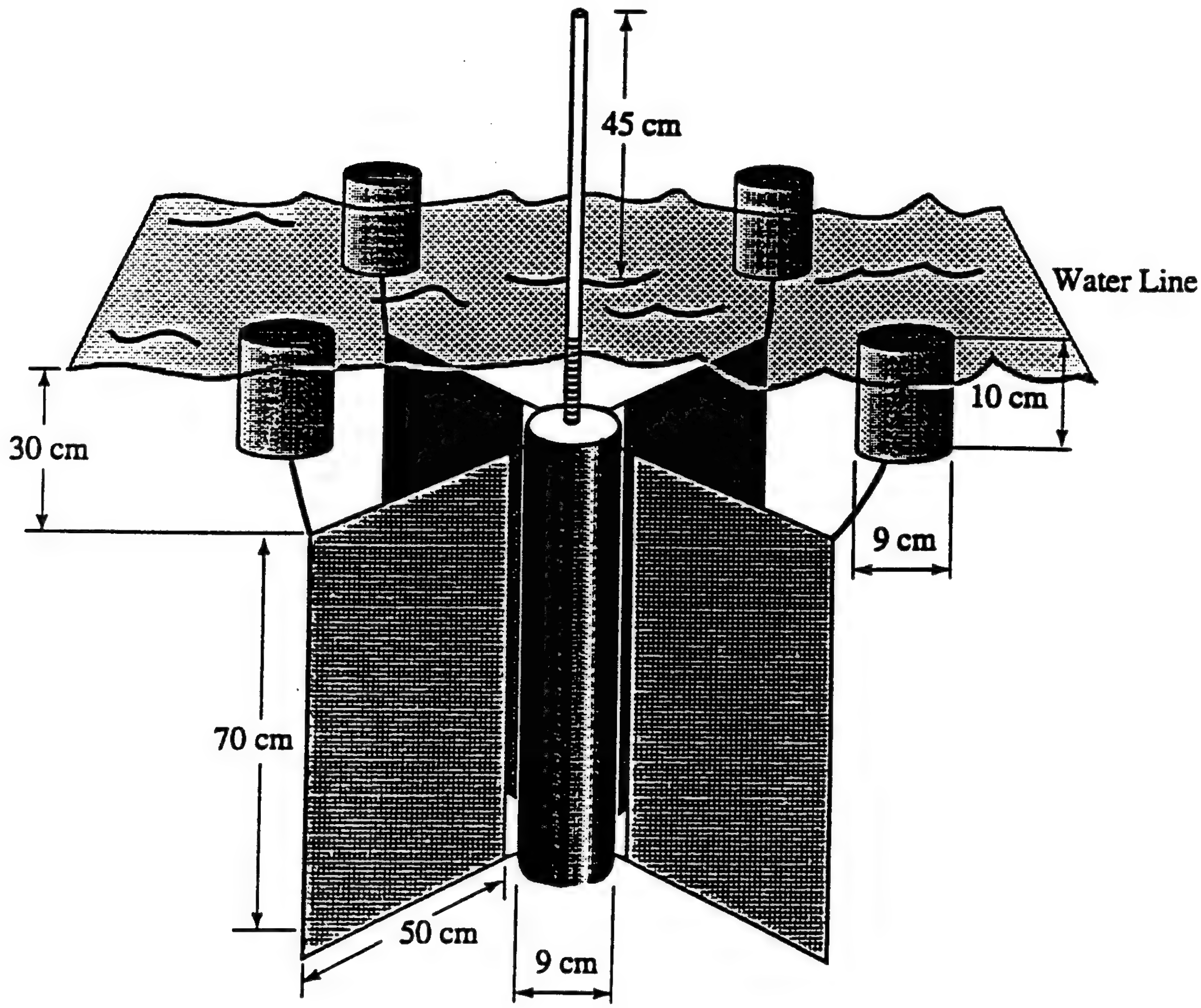


Figure 2-1. $7/10^{th}$ CODE Drifter

2.1.5 Craft Recovery System

Aboard the Cuban Refugee Raft and the surface drifters were Argos transmitters. Positions can be provided through the Argos System for multi-day drifts. For local relocation, a Ginio® 400 Radio Direction Finder (RDF,) tuned to the Argos System frequency (401.065 MHz), was used to direct the work vessel to the leeway craft and the surface drifters.

2.2 TEST CRAFT

2.2.1 Cuban Refugee Raft without a Sail

After examining about fifty rafts that had been used by Cuban refugees, a raft was constructed from 2"x4" wooden boards, plywood, and two aircraft inner tubes. The design is shown in Figure 2-2. The raft was 2.1m long, 1.1m wide, and 0.2m thick. The configuration without a sail was used to estimate the lower leeway rate for Cuban Refugee Rafts. This raft was loaded only with our equipment. The raft contained a GPS positioning system, a leeway measuring system, and an Argos beacon. The anemometer height was 2.0 meters above the water line. A raft of this size has held up to five refugees. Raft loading was lighter than potential loading.

2.2.2 Cuban Refugee Raft with a Sail

The wind monitoring system was removed from the raft and a mast and sail were added. The sail was 1.1 m wide, and extended from a 1.9m height to the deck of the raft. The positioning and leeway systems remained unchanged. This configuration, Figure 2-3, was used to estimate the higher rate for the leeway of Cuban Refugee Rafts.

2.2.3 Commercial Fishing Vessel with Rear-reel for Net Fishing

The Fishing Vessel LITTLE GLEN was used for the work vessel. The leeway of the F/V LITTLE GLEN was also used to determine the leeway of a medium displacement fishing vessel. The F/V Little Glen was a 15 meter long, forward cabin, rear-reel commercial fishing vessel used for net fishing, (Figure 2-4). The F/V LITTLE GLEN was typical of Florida net and long-liners. Florida long-liners have more superstructure over the aft deck then the rear reel net boats. However, the hull and cabin shape are similar.

A wind monitoring system was mounted on the starboard side of the cabin at a height of 6.25 meters above the water line. The anemometer was 2.6 meters above the top of the cabin. A GPS positioning system was installed onboard to track the drift of the F/V LITTLE GLEN. An S4® EMCM in a frame suspended from a float was tethered to the boat to measure leeway.

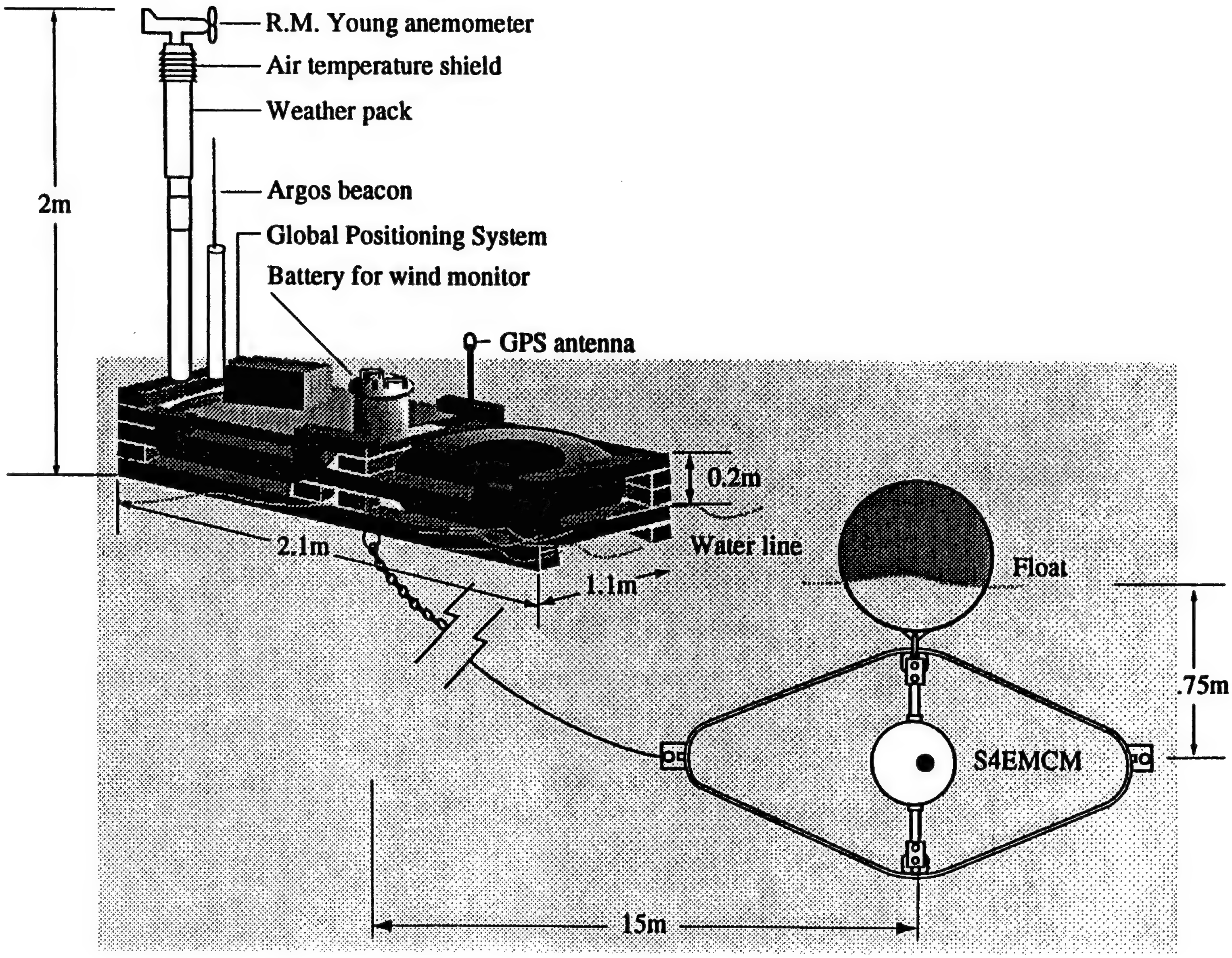


Figure 2-2. Cuban Refugee Raft without a Sail

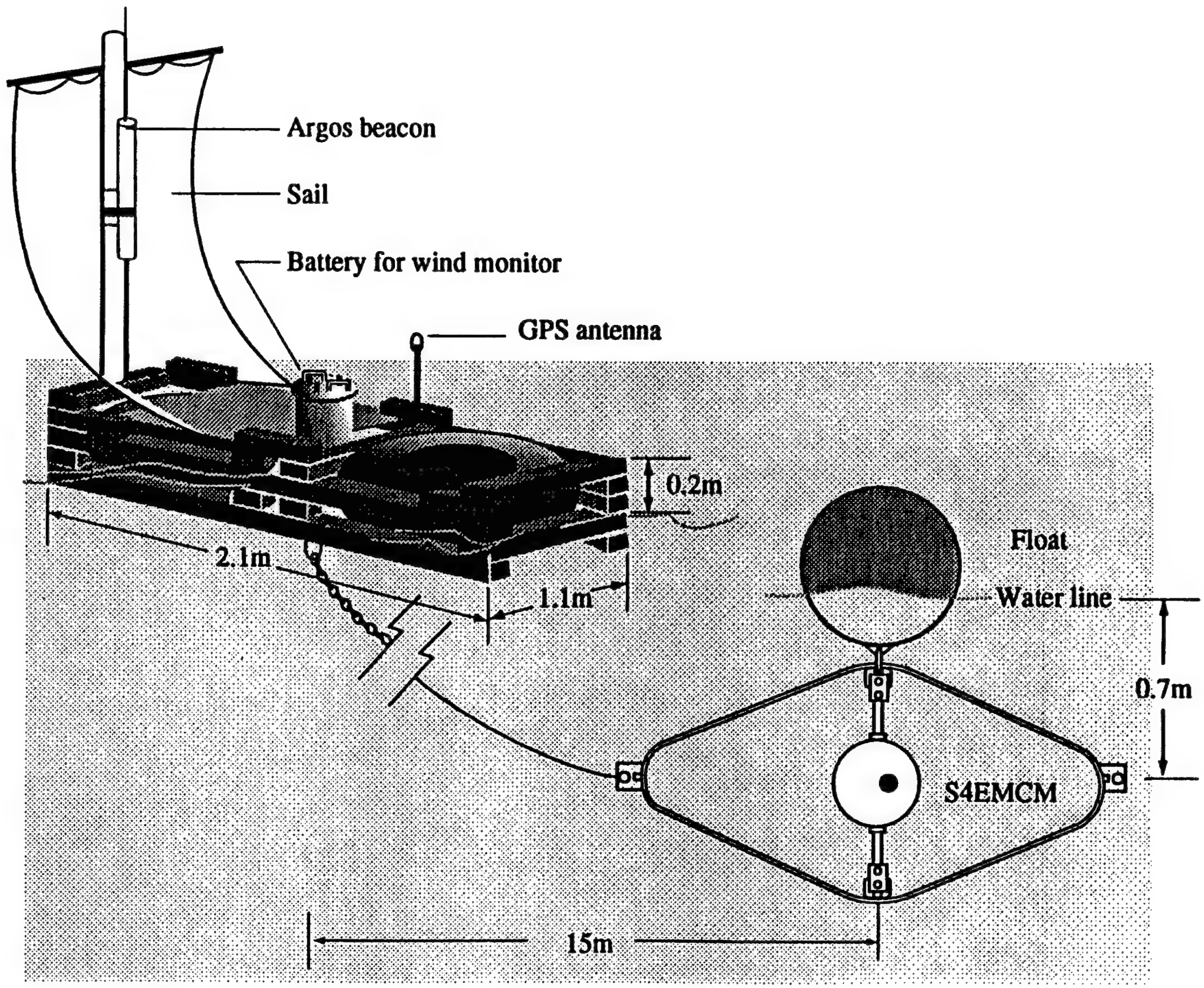


Figure 2-3. Cuban Refugee Raft with a Sail

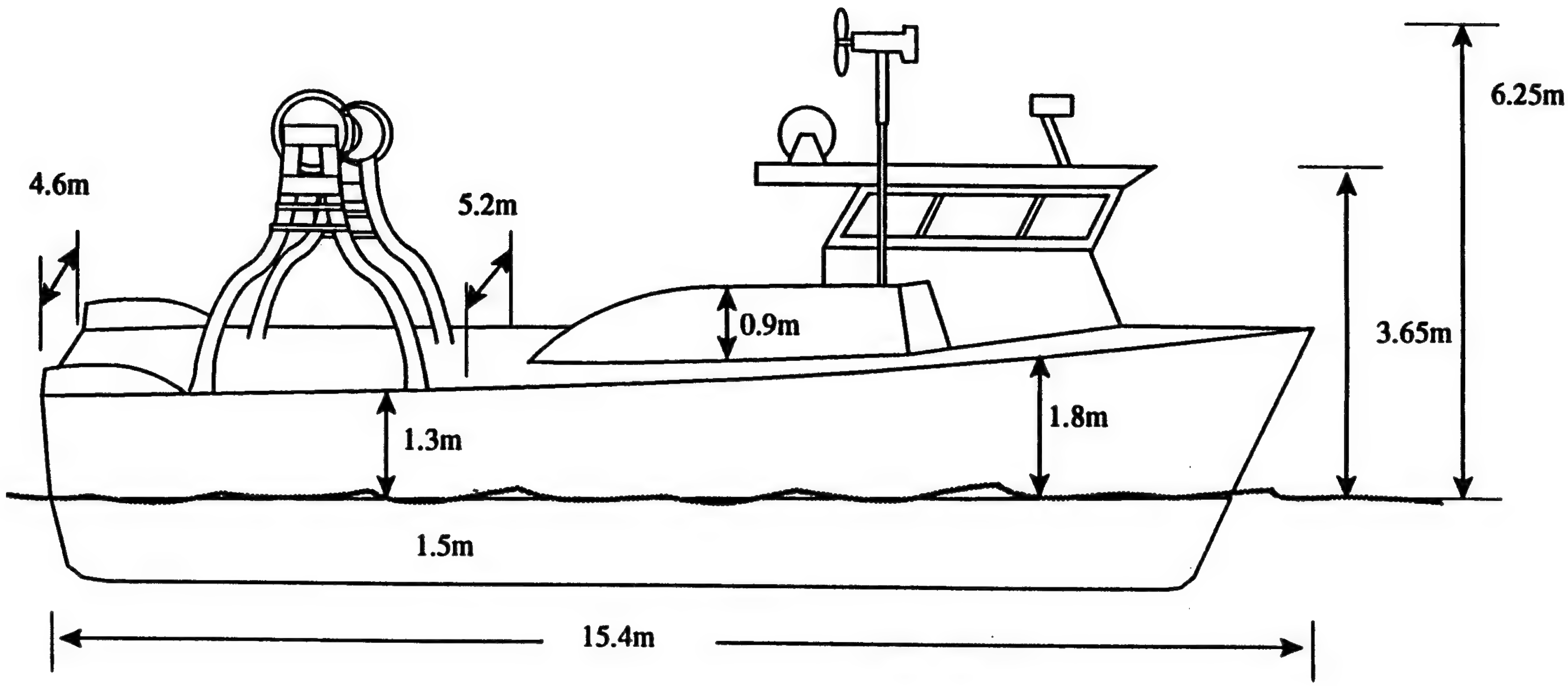


Figure 2-4. The Commercial Fishing Vessel LITTLE GLEN, a 15 meter Rear-reel Net Boat

CHAPTER 3

DATA PROCESSING

3.1 SUMMARY OF DATA REDUCTION

The raw data sets of leeway were edited to include only those sampling intervals when the craft was free drifting and clear of interference. Wind and leeway raw samples are ten minute vector averages. The basic procedures followed Fitzgerald et al. (1993) and Fitzgerald et al.(1994). Time is expressed in Universal Coordinate Time (UTC) and at the center of the 10 minute sample.

Raw Wind data were rotated (+4.69 degrees) from magnetic to true coordinates, and then rotated 180 degrees to convert from the meteorological to the oceanographic convention. This generated the Apparent Winds. The Apparent Winds were not corrected for the motion of the leeway craft. Apparent Winds were then converted to Corrected Winds by adding the drift of the craft. A linear fit was made to the GPS positions for each leeway run. From this, a velocity correction was made to the wind components to create the Corrected Winds. Corrected Winds contain both magnitude and directional corrections to the Apparent Winds. Corrected Winds from the two leeway craft were compared to the winds from the MiniMet® buoy. Corrected Winds for each leeway run were then rotated to match the winds from the MiniMet® buoy and were then called the Adjusted Winds. Adjusted Winds contain only directional corrections to the Corrected Winds. The MiniMet's® anemometer had a clean air flow, with minimum buoy motion. The total directional error of wind direction based on the calibration of the MiniMet's® anemometer and compass was estimated to have been plus or minus 2 degrees. In the final step, wind speed from Adjusted Winds, was adjusted from the anemometer level to the 10 meter reference height using the algorithm described by Smith (1981). Table 3-1 provides a summary of this process. The wind vectors adjusted to the 10 meter reference height are referred to in this report as $\mathbf{W_{10m}}$.

Table 3-1
Wind Data Processing

RAW WIND
- Rotated (+4.69°) from magnetic to true coordinates
- Rotated (180°) from meteorological to oceanographic convection
APPARENT WIND
- Magnitude and direction corrections for the motion of the platform
CORRECTED WIND
- Rotated to match MiniMet's® wind
ADJUSTED WIND (W_{10m})
- Magnitude adjusted to 10 meter reference height using Smith (1981) algorithm

The wind data from the MiniMet® buoy were used for the refugee raft with a sail. The wind data from the MiniMet® buoy were also used for Cuban Refugee Raft without a sail for November 1 and 2 runs. During the first deployment of the raft on 1 November, the raft was deployed upside-down, ducking the anemometer. Thereafter, the raft winds were low and off by 30 degrees compared to the MiniMet winds. Therefore, the wind record from the MiniMet® was substituted for raft winds on 1 and 2 November. The wind speed and north and east components of wind were spline interpolated from 30 minute intervals to ten minute intervals. Wind records were then matched in time to the leeway runs.

The 10 minute averages from the S4® EMCMs were used for leeway and were edited by removing the portions of records before and after the leeway runs. Then the records were rotated +4.69 degrees to convert from magnetic north to true north. Then the velocities were rotated 180 degrees, to convert the relative motion of the water past the current meter to true motion of craft through the water. The leeway records were synchronized with the wind records and combined together into arrays.

The GPS position records used to track the drift of the craft were also edited to remove the portions before and after the actual drift.

Leeway data were matched in time with the corresponding wind data. Leeway angle, downwind, and crosswind components of leeway were calculated by using the Corrected-Adjusted Wind Direction of the corresponding 10 minute winds. Leeway rate was calculated using W_{10m}.

3.2 SUMMARY OF THE DATA SET

Table 3-2 provides a summary of the data sets by drift run collected during the field work. Wave height is significant wave height measured by the MiniMet® buoy.

Table 3-2
Summary of Individual Drift Runs
Fort Pierce, FL OCT/NOV 1994

DATE (1994)	CRAFT	DATA (hh:mm)	W_{10m} (m/s)	WAVE HGT (m)
25 OCT	LITTLE GLEN	1:50	4.7 - 6.0	0.6 - 0.8
26 OCT	LITTLE GLEN	2:30	1.4 - 3.1	0.5 - 0.6
27 OCT	LITTLE GLEN	1:00	4.4 - 8.8	1.0 - 1.1
	LITTLE GLEN	2:10	4.7 - 7.6	1.0 - 1.1
	Raft w/o Sail	2:30	4.5 - 7.6	1.0 - 1.1
28 OCT	LITTLE GLEN	3:00	1.3 - 2.5	1.2 - 1.3
	LITTLE GLEN	1:30	3.3 - 4.5	1.2 - 1.3
	Raft w/o Sail	2:30	1.7 - 2.4	1.2 - 1.3
	Raft w/Sail	1:20	2.9 - 4.2	1.2 - 1.3
31 OCT	LITTLE GLEN	2:30	4.6 - 5.6	1.1 - 1.4
	LITTLE GLEN	2:00	3.8 - 4.8	0.9 - 1.0
	Raft w/Sail	3:00	4.7 - 5.9	1.1 - 1.4
	Raft w/Sail	2:10	3.9 - 4.7	0.9 - 1.0
1 NOV	LITTLE GLEN	2:10	3.8 - 5.1	0.5 - 0.6
	LITTLE GLEN	1:50	3.8 - 5.8	0.5 - 0.6
	Raft w/o Sail	2:20	3.6 - 5.0	0.5 - 0.6
	Raft w/o Sail	1:50	3.6 - 5.7	0.5 - 0.6
2 NOV	LITTLE GLEN	2:40	4.6 - 5.9	0.8 - 0.9
	LITTLE GLEN	2:20	4.5 - 6.5	0.9 - 0.9
	Raft w/o Sail	6:00	4.2 - 6.5	0.8 - 0.9
3 NOV	LITTLE GLEN	4:00	6.2 - 7.0	1.0
	Raft w/Sail	5:00	5.8 - 6.5	1.0

Table 3-3 summarizes total leeway data collected for the three SAR craft.

Table 3-3
Summary of Total Drift Runs
Fort Pierce, FL OCT/NOV 1994

CRAFT	DATA (hh:mm)	W_{10m} (m/s)	WAVE HGT (m)
Raft w/o Sail	15:30	1.7 - 7.6	0.5 - 1.3
Raft w/Sail	11:30	2.9 - 6.5	0.5 - 1.3
F/V LITTLE GLEN	29:30	1.3 - 8.8	0.5 - 1.3

3.3 ANALYSIS METHODOLOGY

3.3.1 Reference Levels and the Definition of Leeway

The definition of leeway used for this work is presented in section 1.2.1. The analysis of the SAR object leeway is presented relative to the water depth at 0.75 meters in terms of the wind velocity corrected for each platform's motion, adjusted to a reference height of 10 meters.

The units used in this report are meters (m) for height and depth, meters per second (m/s) for wind speed, centimeters per second (cm/s) for leeway speed and the leeway components, degrees for angular measurements, degrees Celsius for air and water temperatures and time is the Universal Time Coordinate (UTC) hour of the day. Table 3-4 provides conversion factors for metric to and from English units. Local time was UTC+4 hours for 25 - 28 October, and UTC+5 for 31 October and 1-3 November.

Table 3-4
Conversion Factors for Units

To Convert from	To	Multiply by
meters	feet	3.2808399
m/s	Knots	1.9438462
cm/s	Knots	0.0194385
Knots	m/s	0.514444
Knots	cm/s	51.4444

3.3.2 Definitions of Parameters

Relative Wind Direction is the direction from which the wind blows, measured in degrees about a chosen axis and reference point of the test craft. Values for relative wind direction increase from -180 degrees through zero to +180 degrees with a clockwise rotation of the craft's fore and aft line relative to the downwind direction, Figure 3-1. The convention for boats is to use the fore-and aft line as the axis and the bow as the zero reference point. Thus, wind blowing over the port side of craft has negative relative wind direction and wind over the starboard side is positive. The relative wind direction quantifies the orientation of the craft to the wind direction. Changes in the relative wind direction are generally associated with changes in leeway angle (divergences). Major changes (jibes) can result in the leeway angle changing sign. Jibes are easily noticed in the data sets with relative wind direction convention since the stern passes between -180 and +180 degrees.

Leeway Angle is defined as leeway direction minus wind direction with a deflection to the right of downwind being positive and to the left being negative. This is the same convention as relative wind direction. A leeway angle of 0 degrees indicate that the craft drifts directly downwind. Leeway angles at very low wind speeds are difficult to measure. Therefore leeway angles at low wind speed tend to contain a lot of scatter.

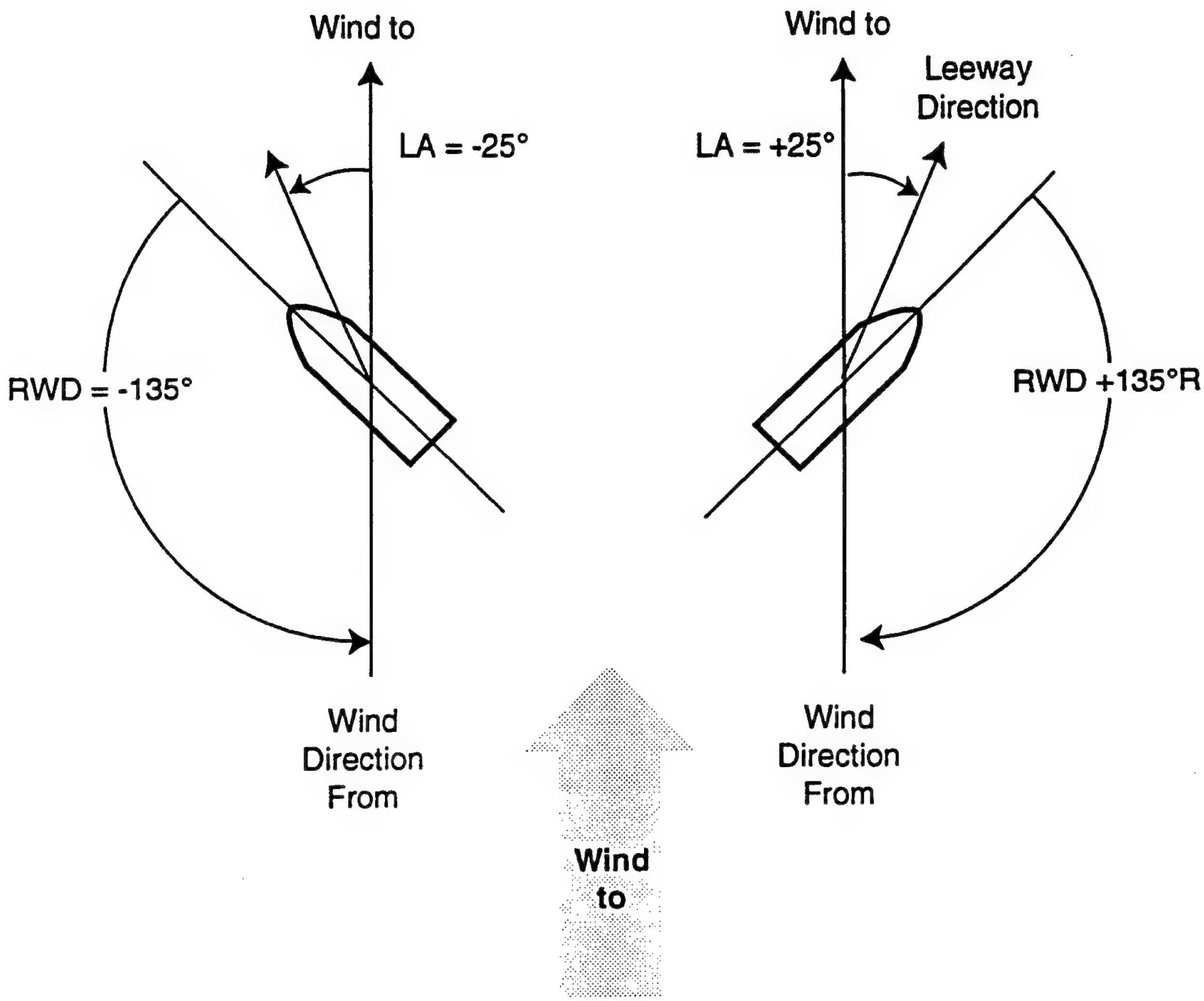
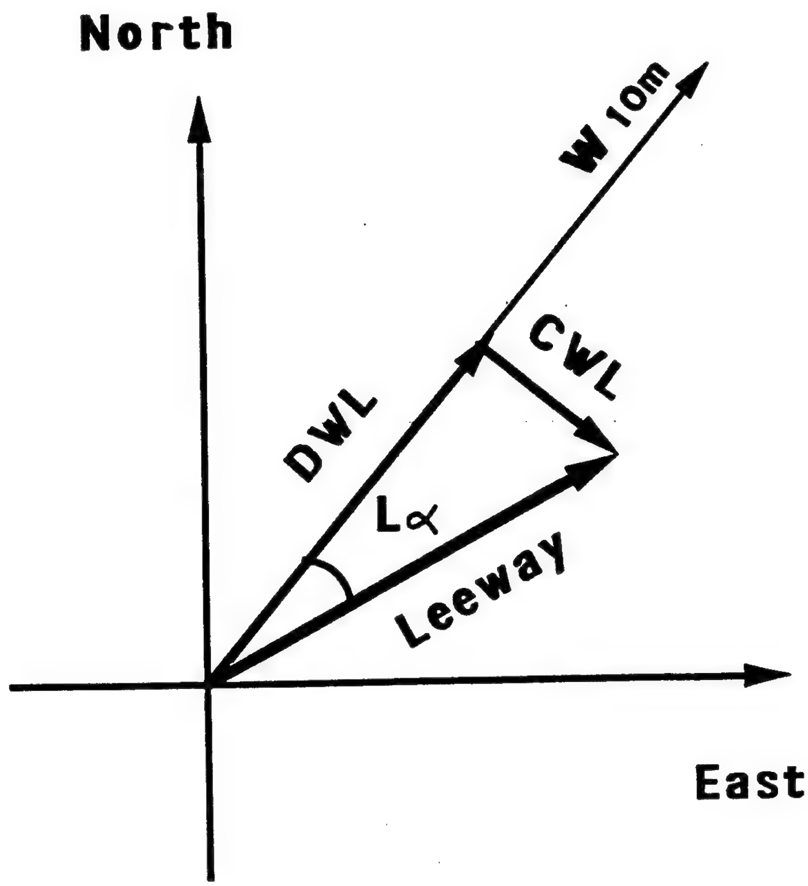


Figure 3-1. Relation of Relative Wind Direction (RWD) and Leeway Angle (Lα)

Leeway speed is the magnitude of the leeway velocity. Leeway speed is always positive. Leeway speed and leeway angle are the polar coordinates for the leeway velocity vector.

Downwind and Crosswind components of Leeway are the components of the leeway velocity vector expressed in rectangle coordinates relative to the wind velocity vector (i.e. $\mathbf{W}_{10m}$), (Figure 3-2). The two components of leeway can be positive or negative. However, as a practical mater, the downwind component of leeway is almost always positive. The crosswind component is the divergence of the SAR craft from the downwind direction. Positive crosswind components are divergence to the right of wind and negative crosswind components are divergence to the left of the wind. One clear advantage of using crosswind components of leeway rather than leeway angle to express the divergence of SAR craft from the downwind direction comes at low wind speeds. Since crosswind components of leeway are multiplied by wind speed, the scatter in the crosswind component is reduced compared to the scatter of leeway angles at low wind speeds.

Leeway rate is defined as the leeway speed ($|\mathbf{L}|$) divided by the wind speed adjusted to the 10 meter reference level ($\mathbf{W}_{10m}$). Taking into account that the unit of $|\mathbf{L}|$ are cm/s and the units of $\mathbf{W}_{10m}$ are m/s, the result has units of a percentage of the wind speed.



W_{10m} = Wind velocity vector adjusted to 10m height,
L = Leeway vector,
$L\alpha$ = Leeway angle,

$\frac{|L|}{|W_{10m}|}$ = Leeway rate,

DWL = $|L|\sin(90^{\circ} - L\alpha)$ = Downwind Leeway component,

CWL = $|L|\cos(90^{\circ} - L\alpha)$ = Crosswind Leeway component.

Figure 3-2. Relationship between the Leeway Speed and Angle and the Downwind and Crosswind Components of Leeway

3.3.3 Statistical Leeway Models

3.3.3.1 Linear Regression of the Mean Values

Two linear regression models of leeway speed and both components of leeway on wind speed were used in this analysis.

$$\text{Leeway} = a + b * \mathbf{W_{10m}} \tag{3-1}$$
(Linear regression)

$$\text{Leeway} = b * \mathbf{W_{10m}} \tag{3-2}$$
(Constrained through zero regression)

where: Leeway represents either leeway speed, downwind component of leeway, or the crosswind component of leeway; $\mathbf{W_{10m}}$ is the wind speed adjusted to the 10 meter reference height; and "a" and "b" are regression coefficients. Tables in Chapter 4 contain the regressions of mean values of leeway speed, crosswind and downwind components of leeway on $\mathbf{W_{10m}}$. Each table contains the number of samples (#), the y-intercept (a) and the slope of the regression line (b), the coefficient of determination or variance explained (r^2), the standard error of the estimate ($S_{y/x}$), and the range of wind speeds. The y-intercept (a) is in *cm/s*, the slope (b) is in [(*cm/s*)/(*m/s*)] which is *percent*, and variance explained (r^2) x 100 = *percent* variance explained.

The statistical analysis of the data sets follows the same procedures of Nash and Willcox (1991) and Fitzgerald et al. (1993) and (1994). The linear and constrained through the origin models were fitted to the data using the least-squares method. This means that all coefficients were chosen to minimize the sum of the square of the difference between the observed and predicted leeway values.

The definitions of coefficient of determination (r^2), Equation 3-3, and the standard error of the estimate ($S_{y/x}$), Equation 3-4, are the same as Nash and Willcox (1991) definitions of r^2 and standard error of estimate (Se).

$$r2 = 1 - \frac{\sum\left(Y - \hat{Y}\right)^2}{\sum\left(Y - \bar{Y}\right)^2} \qquad (3\text{-}3)$$

$$S_{y/x} = \left(\frac{\sum\left(Y - \hat{Y}\right)^2}{d.f.}\right)^{1/2} \qquad (3\text{-}4)$$

where: Y is an observed value of the dependent variable,

$\hat{Y}$ is a predicted value of the dependent variable,

$\bar{Y}$ is the mean of the dependent variables,

$\sum$ is the summation sign,

n is the number of points used in fitting the line, and

d.f. is the degrees of freedom used in fitting the line.

The degrees of freedom (d.f.) is defined as the number of data points minus the number of coefficients in the regression equation; thus for Equation 3-1 d.f. = n-2, and for Equation 3-2, d.f. = n-1.

The coefficient of determination (r^2) is the ratio between the variability in the dependent variable explained by the regression line to the original variability around the mean observations, (equation 3-3). The coefficient of determination is usually between zero and one. An r^2 value of one is a perfect regression fit. An r^2 value of zero indicates that the regression statistically equals the mean value of the dependent variable. Generally, regressions with r^2 values less than 0.4 have poor agreement with the data, 0.5 to 0.8 have good agreement, and greater than 0.8 have excellent agreement. However, negative values for r^2 are also possible. When r^2 is negative, the predicted values from the regression are worst than using the dependent variable's mean for the predictions.

Plots of regressions are also presented in figures in Chapter 4. The regressions are of leeway speed, the downwind component, and the crosswind component of leeway regressed onto the wind speed

adjusted to the 10 meter height. Both linear and constrained through the origin regressions are presented for comparison. In addition, for each regression line, the 95% prediction limits are presented in the figures using methods presented in Neter, Wasserman and Kutner, 1990, (pages 82 and 168). Prediction limits are used to estimate (with 95% confidence) the upper and lower limits for the next individual outcome (the leeway speed or component) at an estimated wind speed. If we were to repeat these experiments and collect a second set of data, then confidence limits would be used to predict the mean of a new regression line. Prediction limits are necessarily wider than confidence limits as prediction limits predict *individual outcomes* and confidence limits estimate *means*. However, our purpose is to use the present data set to make predictions at specific wind speeds for the leeway of these SAR target types, therefore prediction limits at the 95% confidence level are presented along with each regression line.

The data set for a SAR object may contain both positive and negative values for the crosswind component of leeway, since the data set contains multiple runs. Drift runs to the right of the wind produce positive crosswind components and drift runs to the left of the wind produce negative crosswind components. The typical relationship of the crosswind components with increasing wind speed is to be near zero until a threshold wind speed is obtained. Above the threshold wind speed, the crosswind component of leeway increases nearly linearly with wind speed and is symmetrical about the downwind direction. When several drift runs of the same SAR object were combined together into one data set, linear regression models were applied to the absolute value of the crosswind component. The linear models are presented in Chapter 4 with two equally possible solutions, one for a drift to right and one for a drift to left of the wind.

Equation 3-1 (linear regression) and 3-2 (constrained through zero regression) are standard leeway equations used in previous studies and currently in use in search planning. Equation 3-2 is simpler to implement and is preferred by the numerical modelers. While these simple models are quite adequate at low to moderate wind speeds, the models may fail at very low and high wind speeds. Some SAR objects appear to exhibit non-linear behavior as the wind speed approaches zero, necessitating the use of a second linear segment. Also, leeway behavior of SAR objects cannot be simply extrapolated over ever-increasing wind speeds. At higher wind speeds the SAR objects can deform, tilt, react to large waves, or drastically change profiles by capsizing.

3.3.3.2 Processing of 95% Prediction Limits

The 95% prediction limits were calculated using methods from Neter, Wasserman and Kutner, 1990, (pages 82 and 168). Prediction limits are used to estimate (with 95% confidence) the upper and lower limits for next individual outcome (the leeway speed or component) at an estimated wind speed. The 95% prediction limits for linear regression were calculated in the following manner:

$$\hat{Y}_h \pm t(1-\alpha/2;n-2)s\left\{Y_{h(new)}\right\} = (1-\alpha)$$ Prediction limits (3-5)

where:

$$s2\left\{Y_{h(new)}\right\} = MSE\left[1+\frac{1}{n}+\frac{\left(X_h-\overline{X}\right)^2}{\Sigma\left(X_i-\overline{X}\right)^2}\right] \quad (3\text{-}6)$$

the Mean Square Error (MSE) is the square of the standard error of the estimate ($S_{y/x}$),

$$MSE = \left(S_{y/x}\right)^2 \quad (3\text{-}7)$$

$\hat{Y}_h$ is the new mean value of the predicted dependent variable;

$s\left\{Y_{h(new)}\right\}$ is the estimated standard deviation of the new prediction;

X_i is the observed value of the independent variable;

$\overline{X}$ is the mean of the observed independent variables;

X_h is the new predicted value of the independent variable;

α is 0.05 for a 95% prediction limits;

t is the Student t distribution of the 1-α prediction limits based on,

n-2 degrees of freedom;

n is the number of points used.

For regression through the origin, the following equations define the 95% prediction limits:

$$\hat{Y}_h \pm t(1-\alpha/2;n-1)s\left\{Y_{h(new)}\right\} = (1-\alpha) \quad \text{Prediction limits} \qquad (3\text{-}8)$$

$$s2\left\{Y_{h(new)}\right\} = MSE\left[1+\frac{\left(X_h-\overline{X}\right)^2}{\Sigma\left(X_i-\overline{X}\right)^2}\right] \qquad (3\text{-}9)$$

The implementation of equations (Eq. 3-5 to 3-9), to determine the 95% prediction limits, require access to both the wind data and the leeway component variable data. To do this for every new leeway prediction is not numerically efficient. Therefore, the following procedure was followed to provide a readily available equations for the 95% prediction limits for numerical applications. Using the above equations, 95% prediction limits were calculated every 0.1 m/s over the appropriate 10 meter wind speed range (0.0 to 8.0 or 10.0 m/s). Then a second order polynomial equation was fitted to each limit over the wind speed range.

$$95\%\ \text{Prediction limit} \cong c_1 * (\mathbf{W_{10m}})^2 + c_2 * (\mathbf{W_{10m}}) + c_3 \qquad (3\text{-}10)$$

where:

- c_1 has units of $cm*s*\ m^{-2}$,
- c_2 has units of $cm*m^{-1}$, and
- c_3 has units of $cm*s^{-1}$

The coefficients of the second order polynomials that describe the 95% prediction limits for the linear regressions are presented for three leeway target types in tables in Chapter 4. The application of 95% prediction limits to the predicted leeway field is the topic of Chapter 5.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 GENERAL

Eight leeway experiments were conducted near Fort Pierce, FL, between 25 October and 3 November 1994. The commercial fishing vessel LITTLE GLEN was used both as a work boat and as a SAR craft for leeway. In addition to the leeway studies, performance studies of SLDMBs were conducted. On a typical day, a morning drift was conducted. Drifters and leeway targets were reset around noon time, followed by an afternoon drift. Each leeway run was started upwind of the MiniMet® buoy and the leeway targets were allowed to freely drift. Distances of the SAR craft from the MiniMet® buoy was 0 - 5 kilometers. The one exception occurred at the end of morning drift on 31 October 1994 when the raft drifted 8km from the MiniMet® buoy.

Winds during the experimental periods were generally light (1.3 - 8.8 m/s) with small waves (0.5 - 1.3 m). On 28 October, winds were very light (1.3 - 4.5 m/s) but a long 9 second swell was coming in from the northeast. During the other days, the waves were typically wind waves of 4-5 seconds with some swell of 7-8 second periods. Wind direction was steady or slowly changing during the experimental periods. There were no passing fronts or squalls during the experiment periods that would cause a rapid shift in wind speed and direction.

4.2 CUBAN REFUGEE RAFT WITHOUT A SAIL

Data for the Cuban Refugee Raft w/o Sail consist of 93 ten minute averages collected during five drift runs. The 10 meter wind speed ranged from 1.7 - 7.6 m/s, with wave heights of 0.5 - 1.3 meters.

The raft was rectangular, with the anemometer mast at the bow, (000°R). A 2"x4" wooden board just aft of the center of the raft had a large eye bolt that protruded below the raft. Attached to this eye bolt was a 2 meter length of chain and the line to the S4® current meter frame. This attachment point for the S4® current meter allowed the raft to set up relative to wind with minimal steering influence by the current meter.

Relative Wind Direction data is available on only two runs, 27 and 28 October, when the onboard Weatherpak® system was working. The anemometer was damaged during deployment of the raft on 1 November, therefore, winds from the MiniMet® buoy were used for the Cuban Refugee Raft w/o Sail for the drift runs on 1 and 2 November 1994.

Relative Wind Direction on 27 October was -154° to -167° and on 28 October was -137° to -120°. As the wind speed increased from 2 m/s to 5-7 m/s, the raft's orientation to the winds changed from -129° to -160°, Figure 4-1.

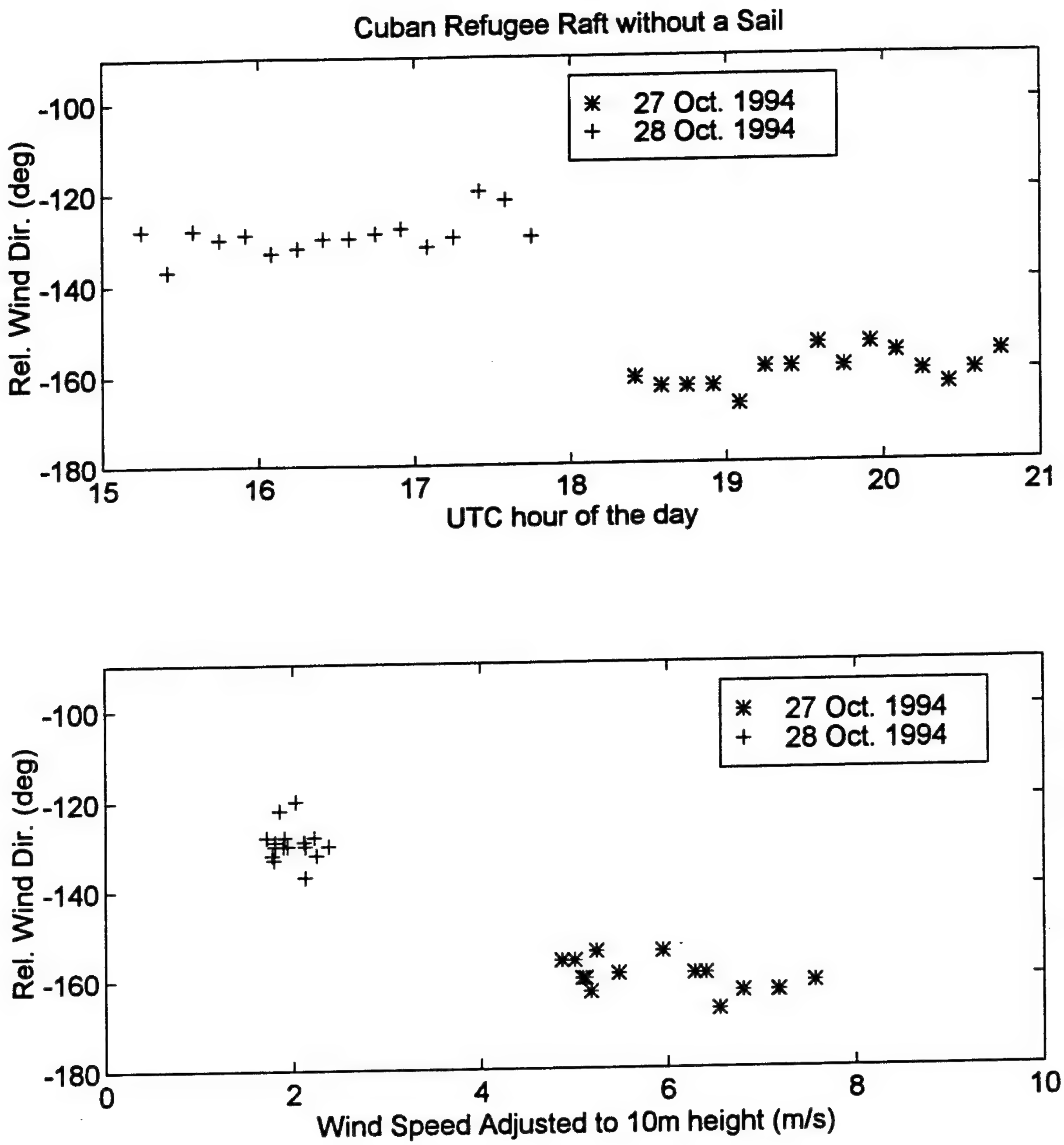


Figure 4-1. (a) Relative Wind Direction time series,
(b) Relative Wind Direction versus Wind Speed at 10m, for Cuban Refugee Raft w/o Sail.

4.2.1 Leeway Angle, Rate and Speed

The leeway angles for the Cuban Refugee Raft w/o Sail were between -28° (left of the wind) and +5° (right of the wind), Figure 4-2. The mean angle was -11°, with a standard deviation of ±6°. The two positive leeway angles occurred at the beginning of deployments. While this particular raft drifted to the left of the downwind direction, there is no reason to believe that all Cuban Refugee rafts would drift to the left of the wind.

The mean leeway rate of the Cuban Refugee Raft w/o Sail was 3.75%, with a standard deviation of ±1.09%, and a range from a minimum of 1.94% to a maximum of 7.23%. There were 93 ten minute data pairs of leeway and W_{10m}.

The leeway speed of the Cuban Refugee Raft w/o Sail for W_{10m} between 2 and 8 m/s is shown in Figures 4-3 and 4-4. The linear regression is shown in Figure 4-3 and the constrained regression in Figure 4-4. The 95% prediction limits are also shown for both regression lines. Linear regression is summarized in Table 4-1 and the constrained regression is summarized in Table 4-2.

Table 4-1

Linear Regression of Leeway Speed (cm/s)
on 10m Wind Speed (m/s)
Cuban Refugee Raft w/o Sail

Dependent Variable	#	a	b	r^2	$S_{y/x}$	W_{10m} (m/s)
Leeway Speed	93	8.74	1.55	0.686	1.52	1.7 - 7.6

Table 4-2

Constrained Regression of Leeway Speed (cm/s)
on 10m Wind Speed (m/s)
Cuban Refugee Raft w/o Sail

Dependent Variable	#	a	b	r^2	$S_{y/x}$	W_{10m} (m/s)
Leeway Speed	93	0.00	3.29	-0.263	3.03	1.7 - 7.6

The coefficient of determination (r^2) of the constrained regression of the leeway speed on W_{10m} was negative.

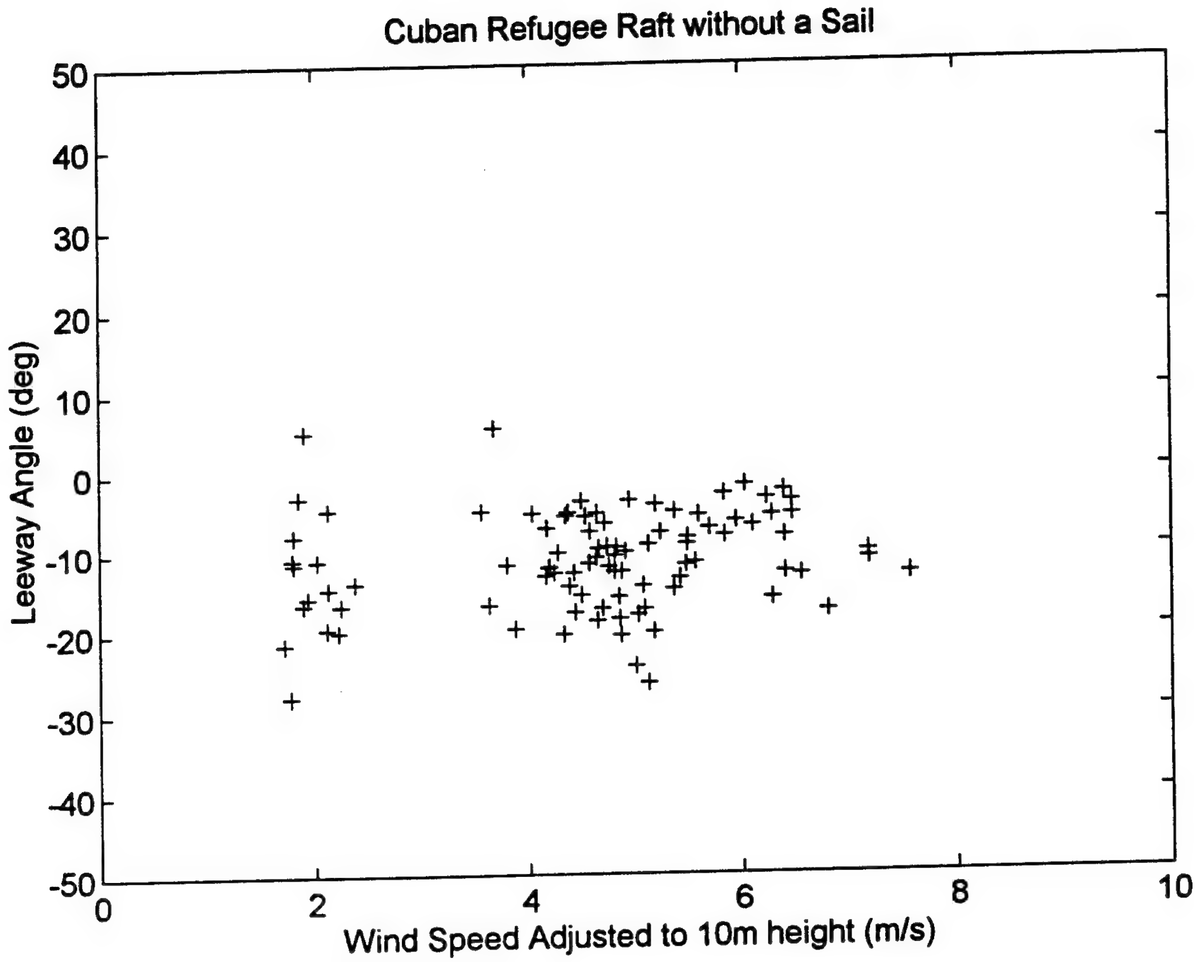


Figure 4-2. Leeway Angle versus Wind Speed at 10m, Cuban Refugee Raft w/o Sail

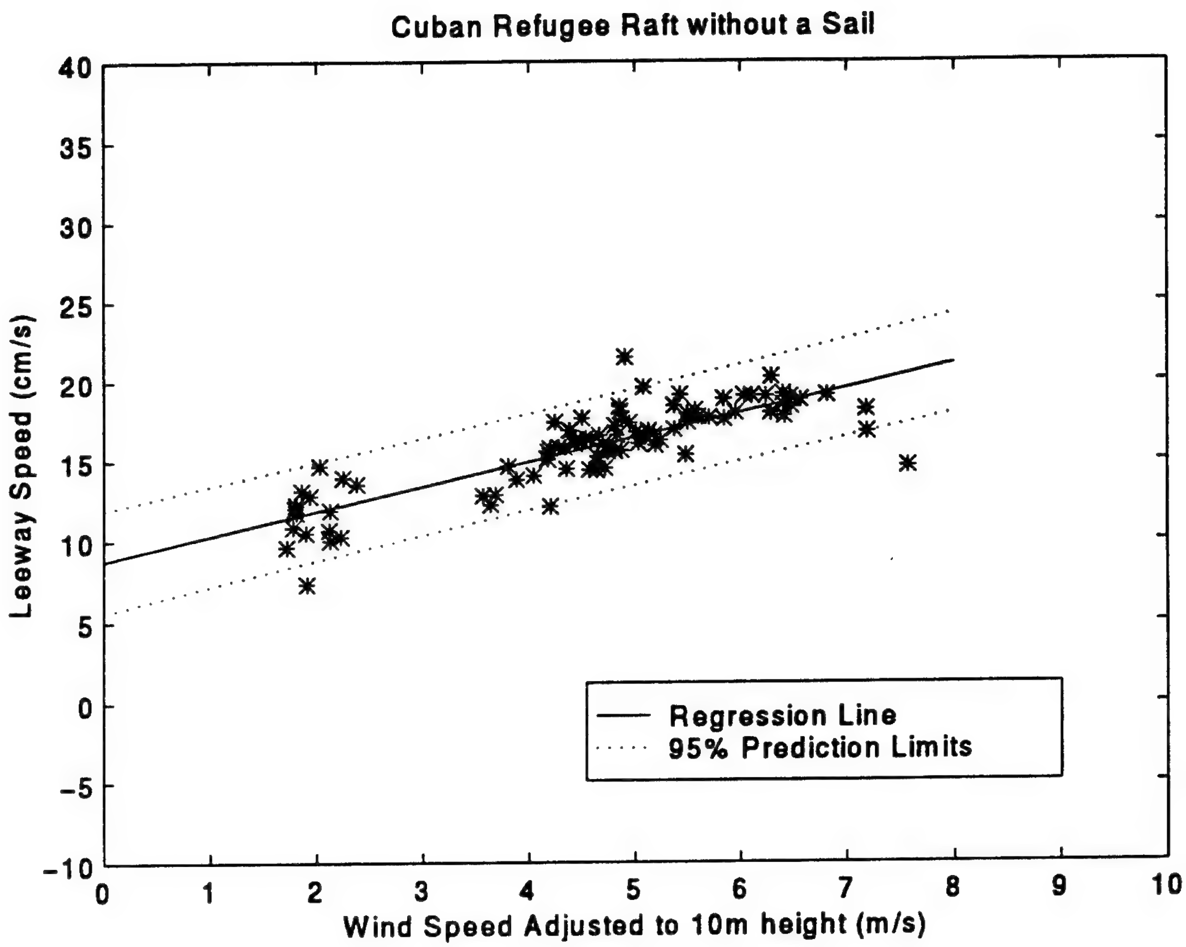


Figure 4-3. The Linear Regression of Leeway Speed versus Wind Speed at 10m, Cuban Refugee Raft w/o Sail.

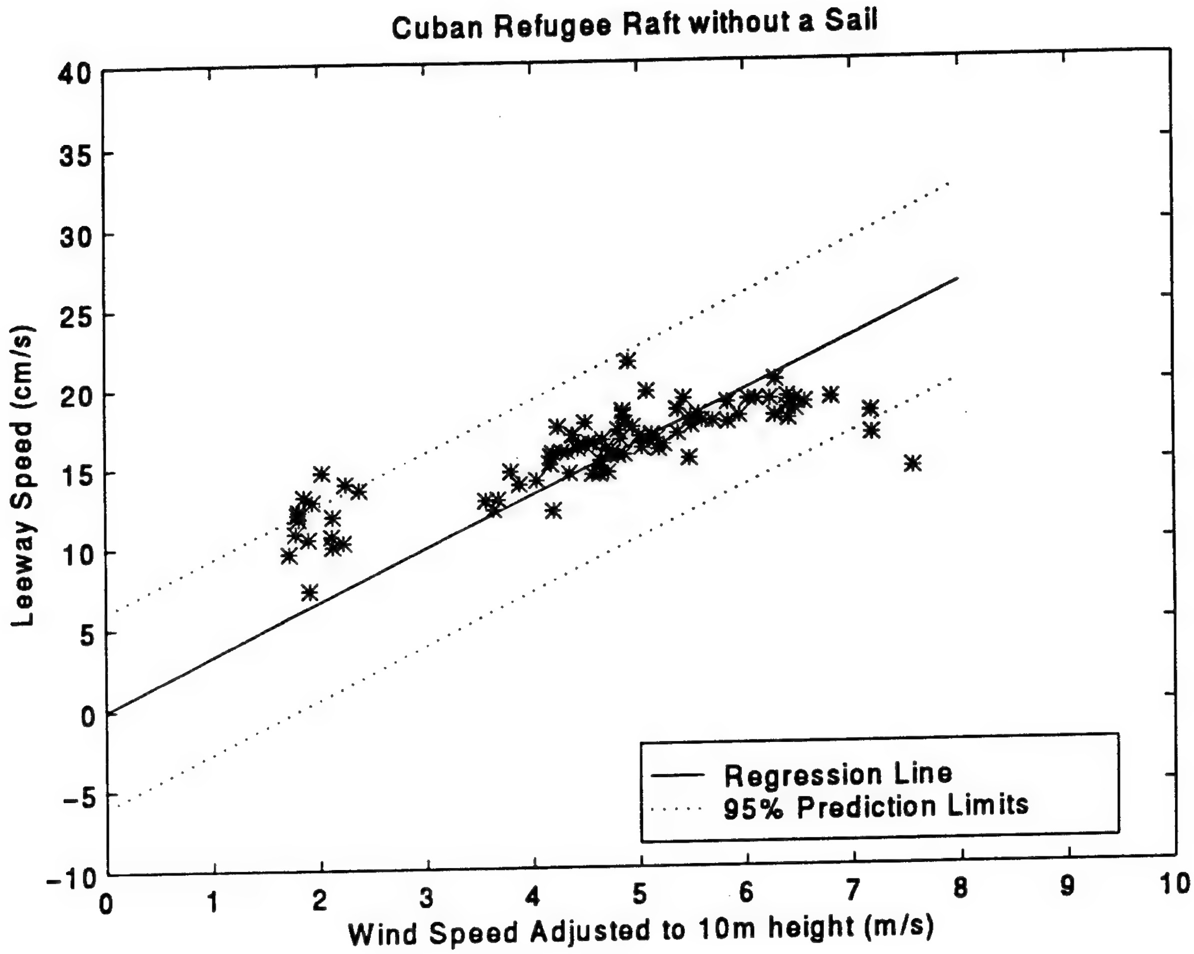


Figure 4-4. The Constrained Regression of Leeway Speed versus Wind Speed at 10m, Cuban Refugee Raft w/o Sail.

4.2.2 Downwind and Crosswind Leeway Components

The downwind and crosswind components of leeway are present in Figure 4-5 through 4-8. The linear and constrained regression lines along with the 95% prediction limits of two leeway components on 10 meter wind speed are also shown in the figures. The coefficients of the mean linear regression are in Table 4-3. The coefficients of the mean constrained regression are in Table 4-4.

Table 4-3

Linear Regression of Leeway Components (cm/s)
on 10m Wind Speed (m/s)
Cuban Refugee Raft w/o Sail

Dependent Variable	#	a	b	r^2	$S_{y/x}$	W_{10m} (m/s)
DWL	93	8.30	1.56	0.686	1.53	1.7 - 7.6
CWL	93	-2.53	-0.11	0.010	1.59	1.7 - 7.6
Abs.(**CWL**)	93	2.70	0.078	0.005	1.52	1.7 - 7.6
-(Abs.(**CWL**))	93	-2.70	-0.078	0.005	1.52	1.7 - 7.6

Table 4-4

Constrained Regression of Leeway Components (cm/s)
on 10m Wind Speed (m/s)
Cuban Refugee Raft w/o Sail

Dependent Variable	#	a	b	r^2	$S_{y/x}$	W_{10m} (m/s)
DWL	93	0.00	3.21	-0.155	2.92	1.7 - 7.6
CWL	93	0.00	-0.61	-0.218	1.76	1.7 - 7.6
Abs.(**CWL**)	93	0.00	0.62	-0.282	1.71	1.7 - 7.6
-(Abs.(**CWL**))	93	0.00	-0.62	-0.282	1.71	1.7 - 7.6

The coefficients of determination (r^2) of the constrained regression of the downwind and crosswind components of leeway on W_{10m} were negative.

The 95% prediction limits were calculated following the procedure described in section 3.3.3.2. The coefficients to Equation 3-10 for the upper and lower 95% prediction limits are presented in Table 4-5 for the linear regression and in Table 4-6 for the constrained regression. The application of these coefficients in equation 3-10 is illustrated in Chapter 5.

Table 4-5

The Coefficients of the Polynomials Describing
95% Prediction Limits of the
Linear Regression of Leeway Components (cm/s)
on 10m Wind Speed (m/s)
Cuban Refugee Raft w/o Sail

Dependent Variable	Upper limits			Lower Limits		
	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3
DWL	0.0078	1.4909	11.5154	-0.0078	1.6328	5.0751
CWL	0.0081	-0.1814	0.8263	-0.0081	-0.0336	-5.8803
Abs.(CWL)	0.0077	0.0078	5.8939	-0.0077	0.1484	-0.4897
-Abs.(CWL)	0.0077	-0.1484	0.4897	-0.0077	-0.0078	-5.8939

Table 4-6

The Coefficients of the Polynomials Describing
95% Prediction Limits of the
Constrained Regression of Leeway Components (cm/s)
on 10m Wind Speed (m/s)
Cuban Refugee Raft w/o Sail

Dependent Variable	Upper limits			Lower Limits		
	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3
DWL	0.0013	3.2117	5.8015	-0.0013	3.2116	-5.8015
CWL	0.0008	-0.6100	3.4918	-0.0008	-0.6101	-3.4918
Abs.(CWL)	0.0008	0.6155	3.4039	-0.0008	0.6154	-3.4039
-Abs.(CWL)	0.0008	-0.6154	3.4039	-0.0008	-0.6155	-3.4039

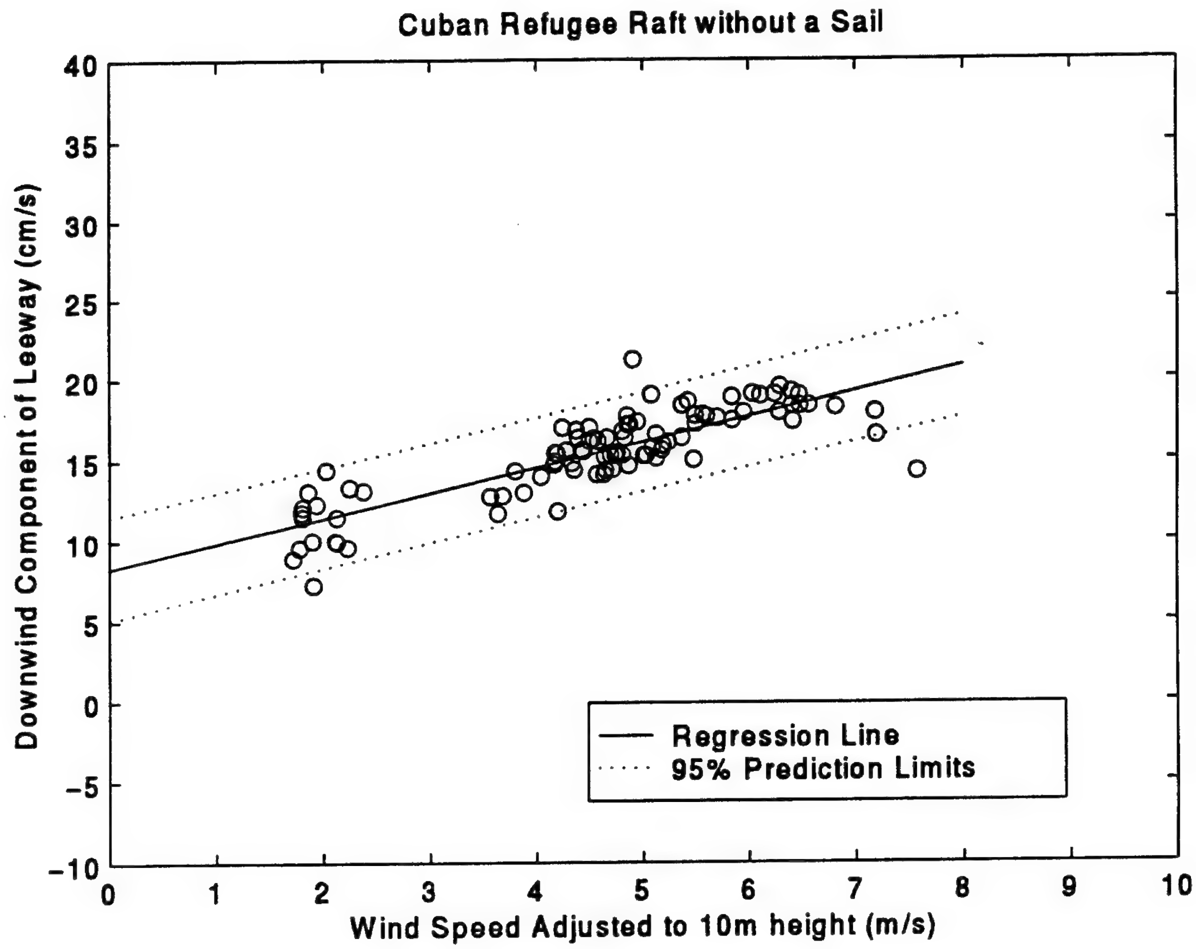


Figure 4-5. The Linear Regression of the Downwind Component of Leeway versus Wind Speed at 10m, Cuban Refugee Raft w/o Sail.

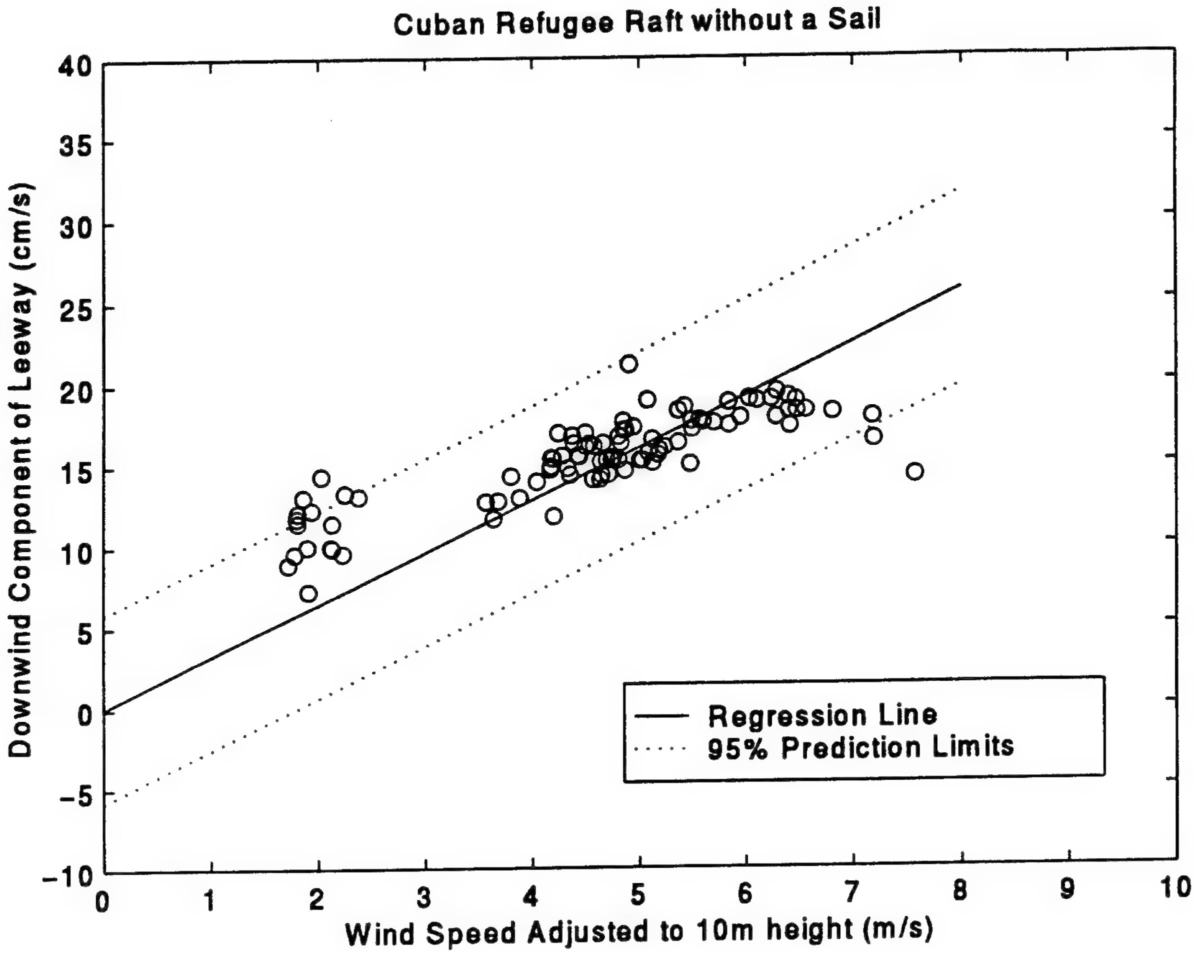


Figure 4-6. The Constrained Regression of the Downwind Component of Leeway versus Wind Speed at 10m, Cuban Refugee Raft w/o Sail.

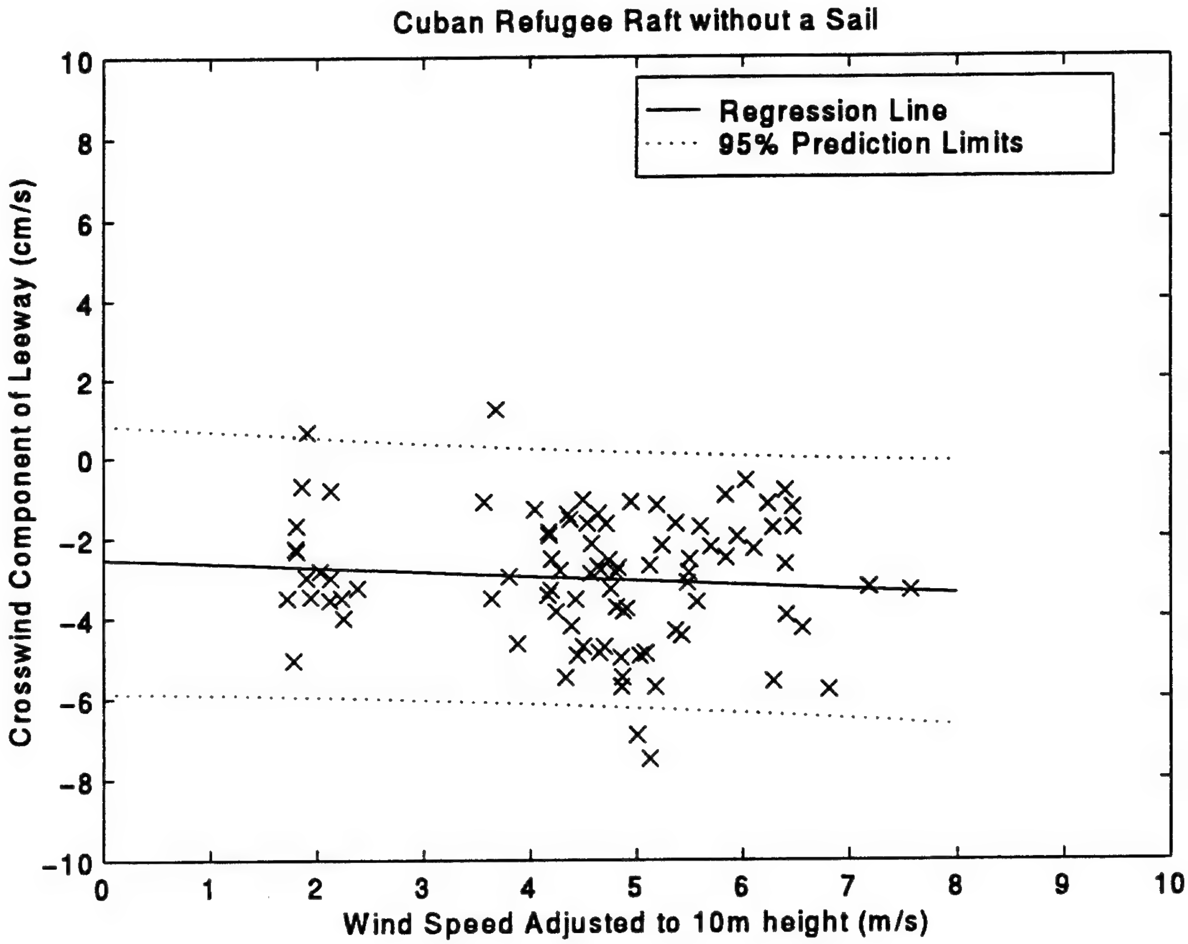


Figure 4-7. The Linear Regression of the Crosswind Component of Leeway versus Wind Speed at 10m, Cuban Refugee Raft w/o Sail.

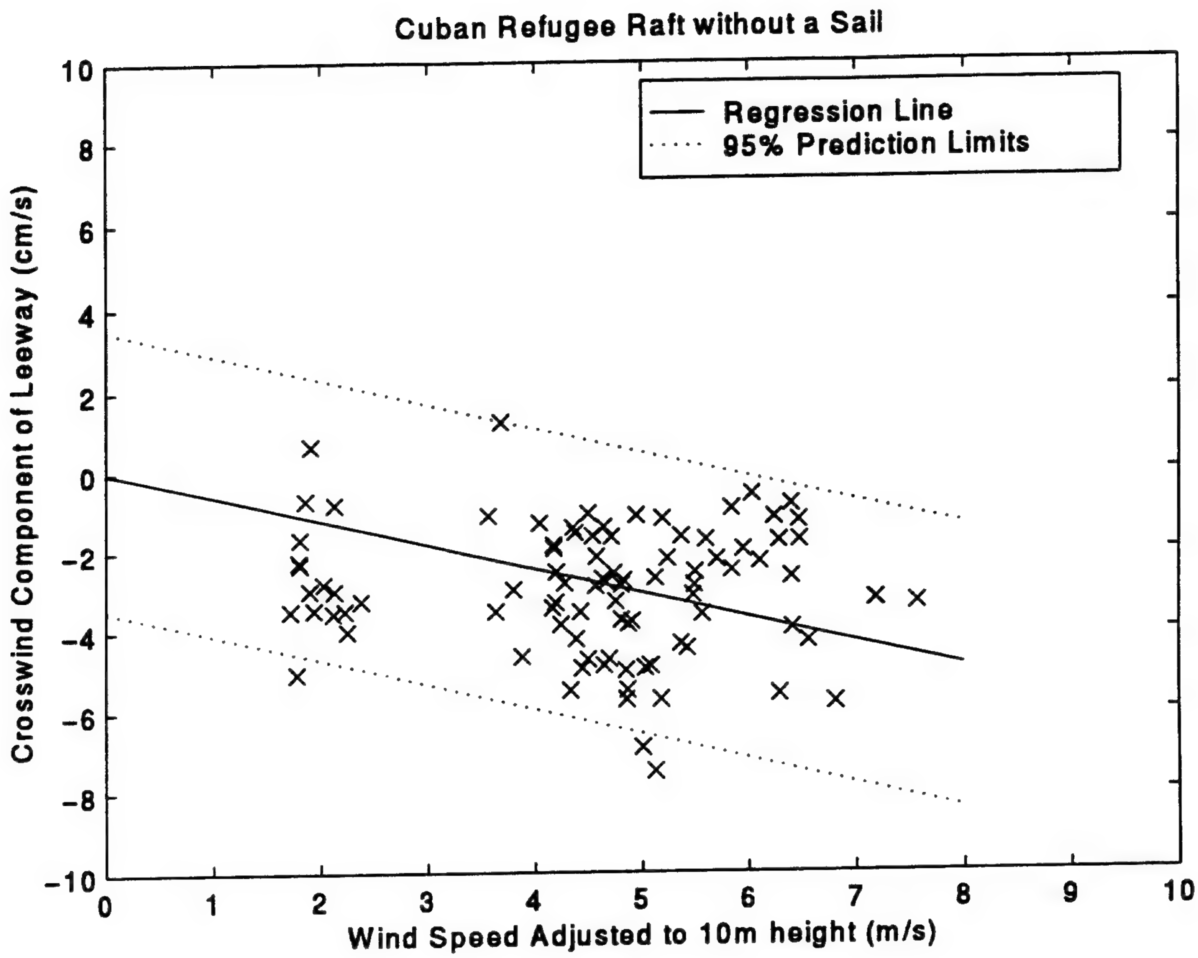


Figure 4-8. The Constrained Regression of the Crosswind Component of Leeway versus Wind Speed at 10m, Cuban Refugee Raft w/o Sail.

4.3 CUBAN REFUGEE RAFT WITH A SAIL

Data for the Cuban Refugee Raft w/Sail consists of 69 ten minute averages collected during four drift runs. The Cuban Refugee Raft w/Sail was the same raft as the Cuban Refugee Raft w/o Sail, modified by replacing the anemometer with a cross bar that supported a simple square rigged sail. Wind data from the MiniMet® buoy was used for determining the 10 meter wind speed at the raft. The range from the raft to the MiniMet® buoy was 0 to 8 kilometers. The 10 meter wind speed ranged from 2.9 - 6.5 m/s, with wave heights of 0.5 - 1.3 meters.

Since the Weatherpak® wind monitor system was removed from the raft, no compass was available to collect heading data. Therefore, there is no relative wind direction data from the Cuban Raft w/Sail.

4.3.1 Leeway Angle, Rate, and Speed

The leeway angle for the Cuban Refugee Raft w/Sail ranged from -43° to +27°, with a mean of -7°, and a standard deviation of 19°, Figure 4-9. The raft with a sail had a larger range of leeway angles than the raft without a sail. Three outliers (at -40°, 6 m/s) occurred at the beginning of the 3 November run. The raft was rigged with a single foresail by two guide lines at the two lower corners of the rectangular sail. On 3 November, one of guide line was pulled further aft on the raft than the other guide line. This changed the sail orientation from the normal "running" configuration to a "broad reaching" configuration. After 30 minutes that guide line apparently loosened, returning the sail to the "running" configuration. Leeway angles then returned to -20° to -30° off the downwind direction. However, this inadvertent changing of the sail configuration raises the possibility that even crude rafts can be sailed off the downwind direction by as much as 40 degrees.

The mean leeway rate of the Cuban Refugee raft w/Sail was 6.16% $\pm$1.01% standard deviation, with a range from 4.15% to 8.90%.

The leeway speed of the Cuban Refugee Raft w/Sail for W_{10m} between 3 and 7 m/s is shown in Figures 4-10 and 4-11. The linear (Figure 4-10) and the constrained regressions (Figure 4-11) of leeway speed on wind speed are shown along with the 95% prediction limits for the regressions. The coefficients for the mean linear regression are in Table 4-7. The coefficients for the mean constrained regression are in Table 4-8.

Table 4-7

Linear Regression of Leeway Speed (cm/s) on 10m Wind Speed (m/s) Cuban Refugee Raft w/Sail

Dependent Variable	#	a	b	r^2	$S_{y/x}$	W_{10m} (m/s)
Leeway Speed	69	-8.88	7.93	0.685	5.38	2.9 - 6.5

Table 4-8

Constrained Regression of Leeway Speed (cm/s) on 10m Wind Speed (m/s) Cuban Refugee Raft w/Sail

Dependent Variable	#	a	b	r^2	$S_{y/x}$	W_{10m} (m/s)
Leeway Speed	69	0.00	6.30	0.655	5.59	2.9 - 6.5

The plots of leeway speed versus wind speed (Figures 4-10 and 4-11) also show the same three outliers (54 cm/s in 6.1 m/s winds) from the beginning of the 3 November run. Apparently, the raft was sailing at 8.6 - 8.9% of the wind speed for about a half an hour at 42° to the left of the downwind direction.

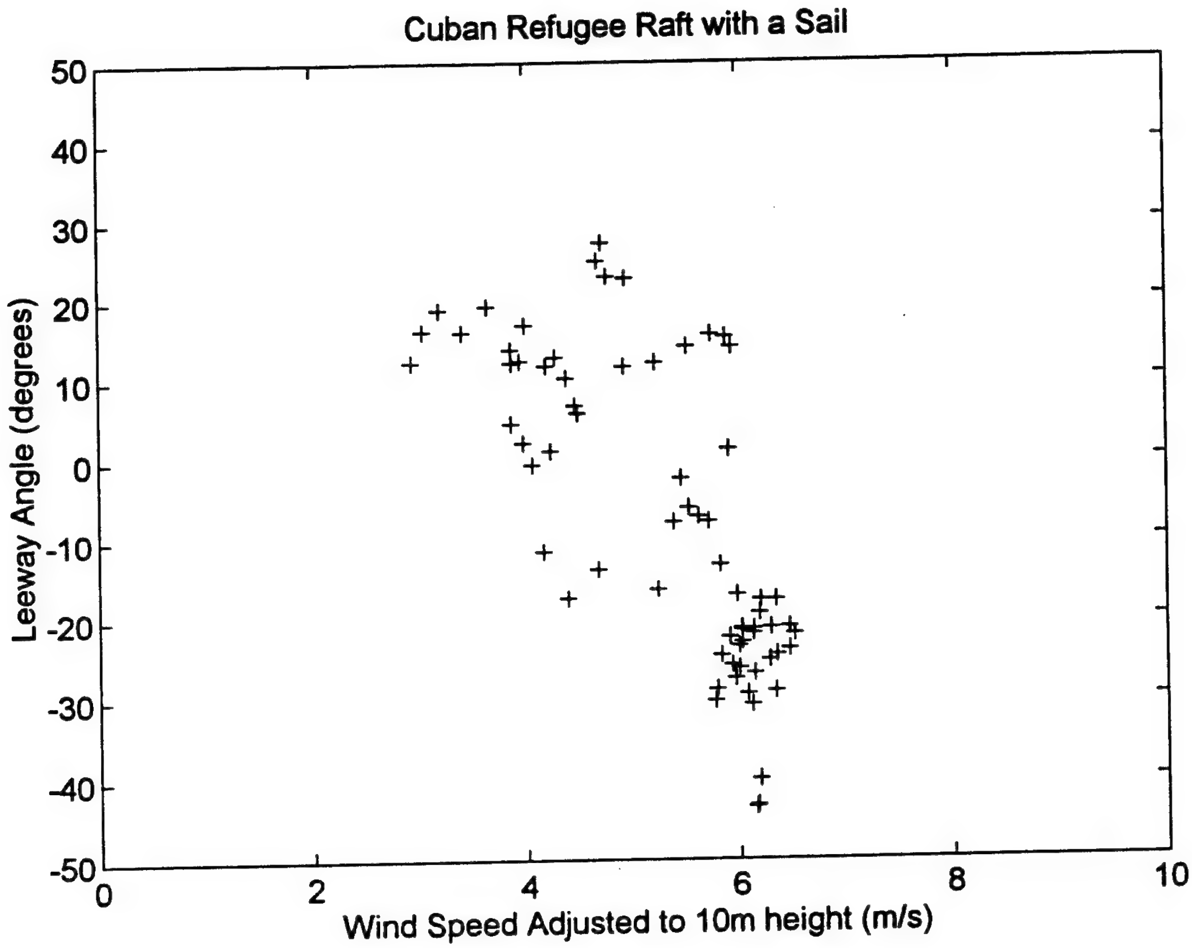


Figure 4-9. Leeway Angle versus Wind Speed at 10m, Cuban Refugee Raft w/ Sail

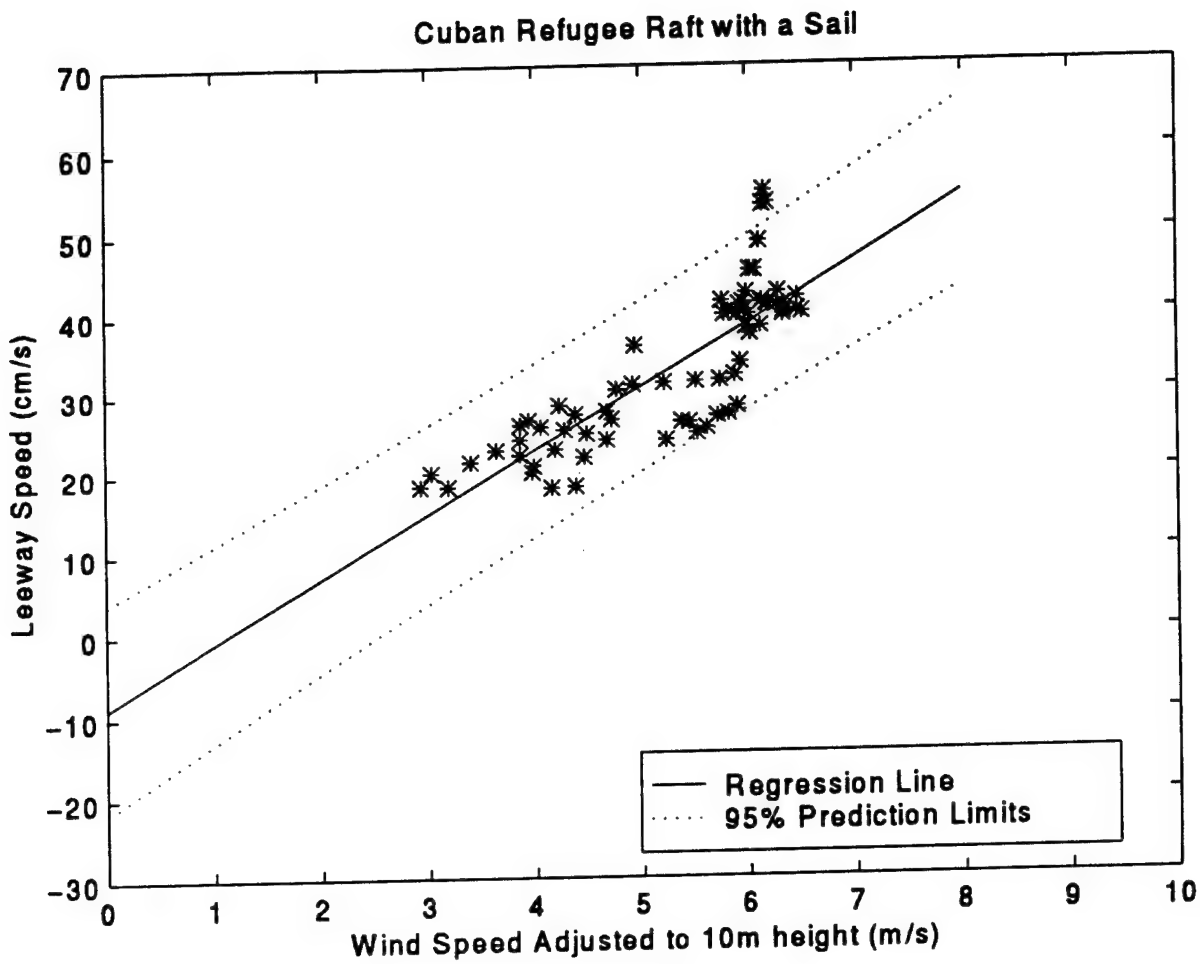
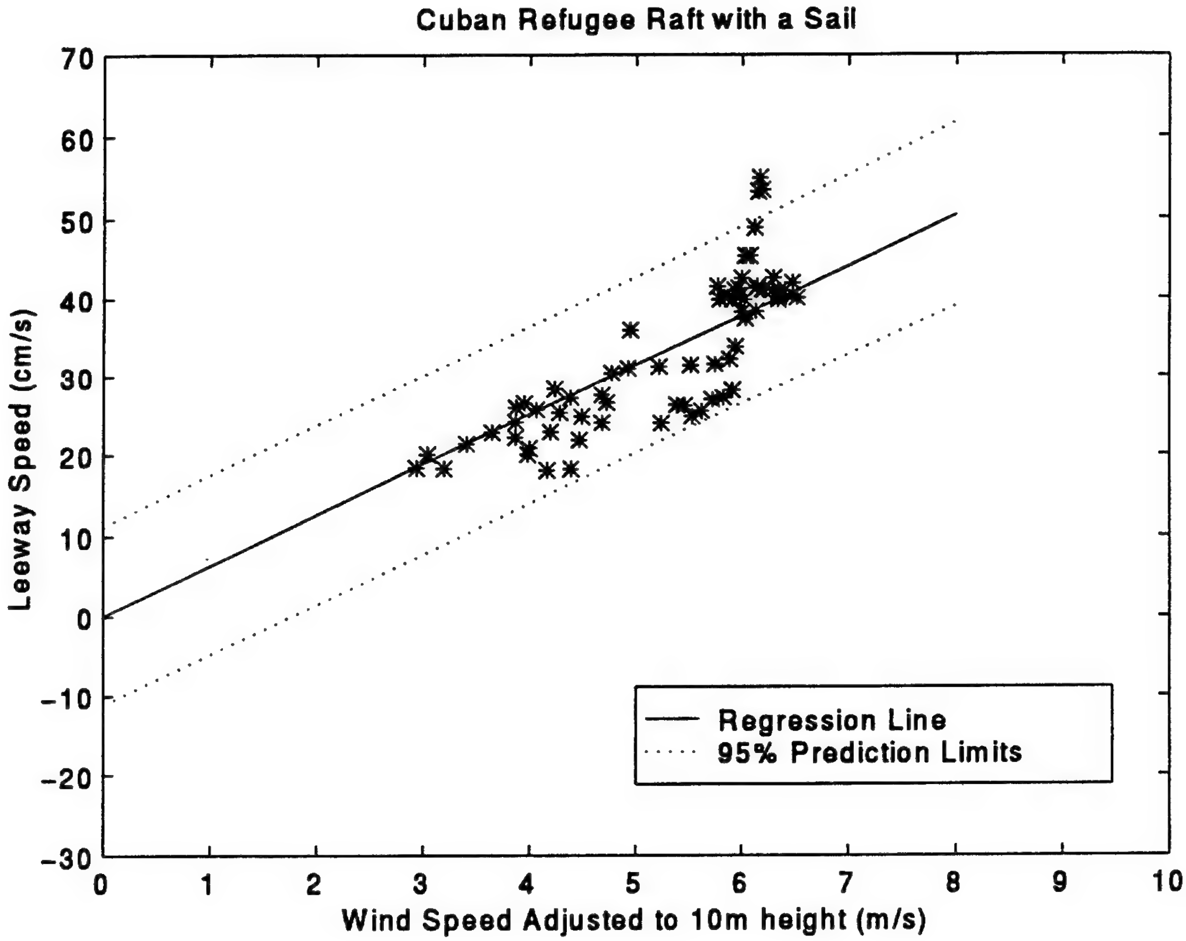


Figure 4-10. The Linear Regression of Leeway Speed versus Wind Speed at 10m, Cuban Refugee Raft w/ Sail.



4-11. The Constrained Regression of Leeway Speed versus Wind Speed at 10m, Cuban Refugee Raft w/Sail.

4.3.2 Downwind and Crosswind Leeway Components

The downwind component of leeway for the Cuban Refugee Raft w/Sail is shown in Figures 4-12 and 4-13. The linear and constrained regression lines along with the 95% prediction limits are also shown in Figures 4-12 and 4-13. The values for the regression models are in Tables 4-9 and 4-10. For W_{10m} between 3 and 7 m/s, both regression models provide similar answers for the downwind component of leeway.

The crosswind component of leeway for the Cuban Refugee Raft w/Sail are shown in Figures 4-14 through 4-18. Time series of the crosswind components are shown in Figure 4-14. Figures 4-15 and 4-16 are the linear and constrained regressions of the crosswind component on the 10m wind speed. Because there were positive and negative crosswind components, both linear and constrained regression line were also fitted to the absolute values of the crosswind component, and are presented in Figures 4-17 and 4-18. The 95% prediction limits for each regression line are also shown. The entire drift run on 3 November 1994 showed crosswind components between -10 and -40 cm/s, while the other three runs were between -10 and +15 cm/s. Evidently, the raft was rigged differently on 3 November resulting in the raft sailing for the first half hour at -36 cm/s to the wind, and then for the rest of drift at -16.6 $\pm$ 3.1 cm/s. During the two runs on 31 October 1994, the raft changed from positive leeway components to negative leeway components, which suggests that the raft jibed twice.

Combining the 57 drift runs conducted by Fitzgerald et at. (1993) and (1994) and the 22 runs conducted during this study, these two jibes were the second and third jibes observed. The crosswind component of the raft apparently was very sensitive to how the sail was rigged. During 31 October leeway drift, the sail was loosely tied, which resulted in the sail shifting and a jibe occurring. On 1 November the sail was rigged off center, which resulted in the raft reaching 18° to 42° left of downwind direction.

The downwind component of leeway for the Cuban refugee raft w/Sail appears be well behaved compared to its crosswind component. The linear regression of the crosswind component (Figures 4-15 and 4-17) clearly fail at W_{10m} less than 2.5 m/s. Therefore, the zero crossing (coefficient "a" in Table 4-9) for the linear regression of the crosswind component is clearly unrealistic.

Table 4-9

Linear Regression of Leeway Components (cm/s)
on 10m Wind Speed (m/s)
Cuban Refugee Raft w/Sail

Dependent Variable	#	a	b	r^2	$S_{y/x}$	W_{10m} (m/s)
DWL	69	-3.47	6.43	0.759	3.63	2.9 - 6.5
CWL	69	40.0	-8.76	0.487	8.99	2.9 - 6.5
Abs.(CWL)	69	-16.2	5.19	0.389	6.50	2.9 - 6.5
-(Abs.(CWL))	69	16.2	-5.19	0.389	6.50	2.9 - 6.5

Table 4-10

Constrained Regression of Leeway Components (cm/s)
on 10m Wind Speed (m/s)
Cuban Refugee Raft w/Sail

Dependent Var	#	a	b	r^2	$S_{y/x}$	W_{10m} (m/s)
DWL	69	0.00	5.80	0.751	3.66	2.9 - 6.5
CWL	69	0.00	-1.44	0.135	11.6	2.9 - 6.5
Abs.(CWL)	69	0.00	2.22	0.257	7.12	2.9 - 6.5
-Abs.(CWL))	69	0.00	-2.22	0.257	7.12	2.9 - 6.5

The 95 percent prediction limits were calculated following the procedure described in section 3.3.3.2. The coefficients to Equation 3-10 for the upper and lower 95% prediction limits are presented in Table 4-11 for the linear regression and in Table 4-12 for the constrained regression. The application of these coefficients in Equation 3-10 is illustrated in Chapter 5.

Table 4-11

The Coefficients of the Polynomials Describing
95% Prediction Limits of the
Linear Regression of Leeway Components (cm/s)
on 10m Wind Speed (m/s)
Cuban Refugee Raft w/Sail

Dependent Variable	Upper limits			Lower Limits		
	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3
DWL	0.0496	5.910	5.2182	-0.0496	6.9572	-12.149
CWL	0.1229	-10.055	61.4848	-0.1229	-7.4605	18.457
Abs(CWL)	0.0889	4.2480	-0.6341	-0.0889	6.1255	-31.770
-Abs.(CWL)	0.0889	-6.1255	31.770	-0.0889	-4.2480	0.6341

Table 4-12

The Coefficients of the Polynomials Describing
95% Prediction Limits of the
Constrained Regression of Leeway Components (cm/s)
on 10m Wind Speed (m/s)
Cuban Refugee Raft w/Sail

Dependent Variable	Upper limits			Lower Limits		
	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3	$c_1 (W_{10m})^2$	$c_2 () W_{10m}$	c_3
DWL	0.0018	5.7991	7.2974	-0.0018	5.7989	-7.2974
CWL	0.0057	-1.4381	23.1195	-0.0057	-1.4388	-23.119
Abs.(CWL)	0.0035	2.2201	14.2011	-0.0035	2.2197	-14.201
-Abs.(CWL)	0.0035	-2.2197	14.2011	-0.0035	-2.2201	-14.201

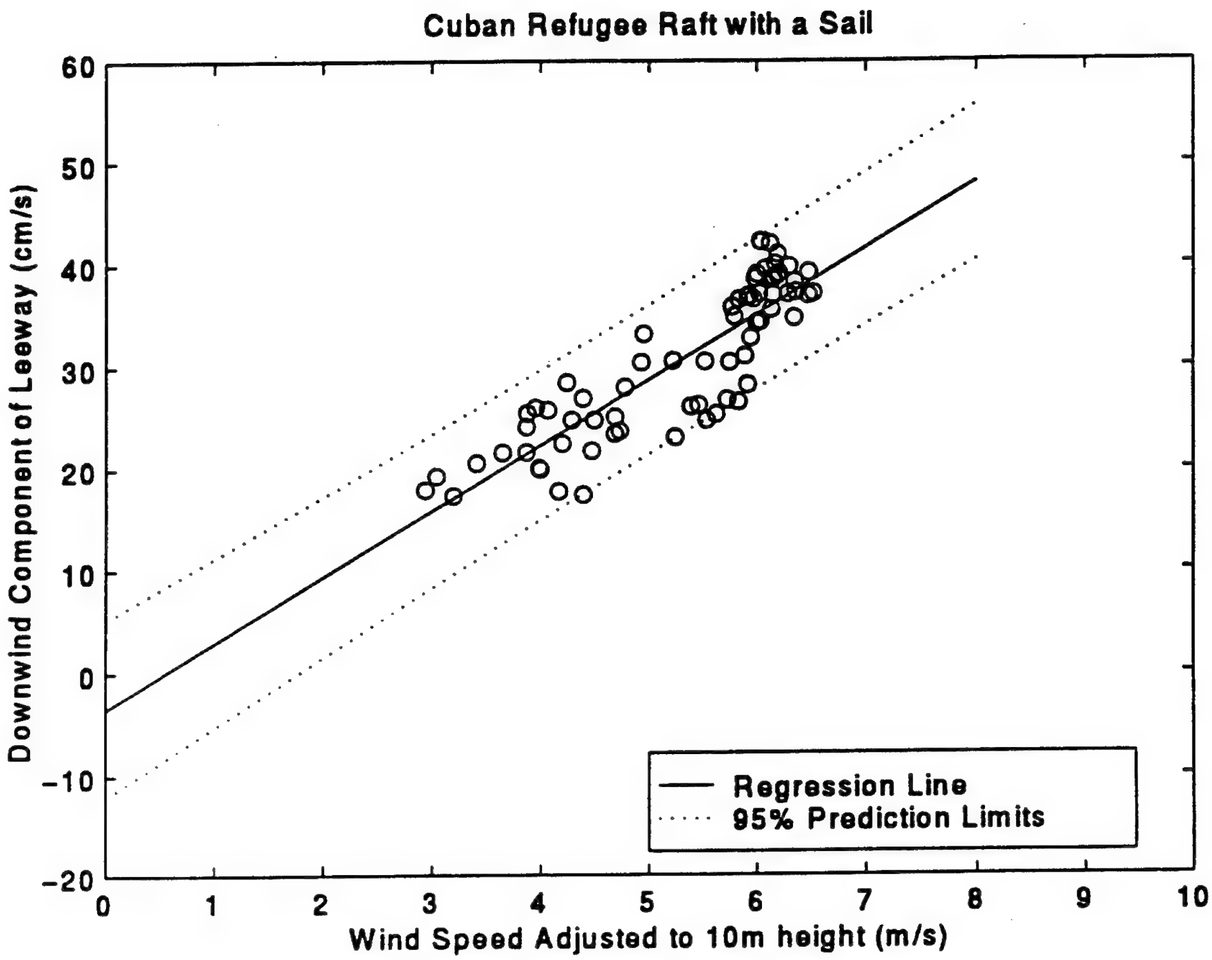


Figure 4-12. The Linear Regression of the Downwind Component of Leeway versus Wind Speed at 10m, Cuban Refugee Raft w/ Sail.

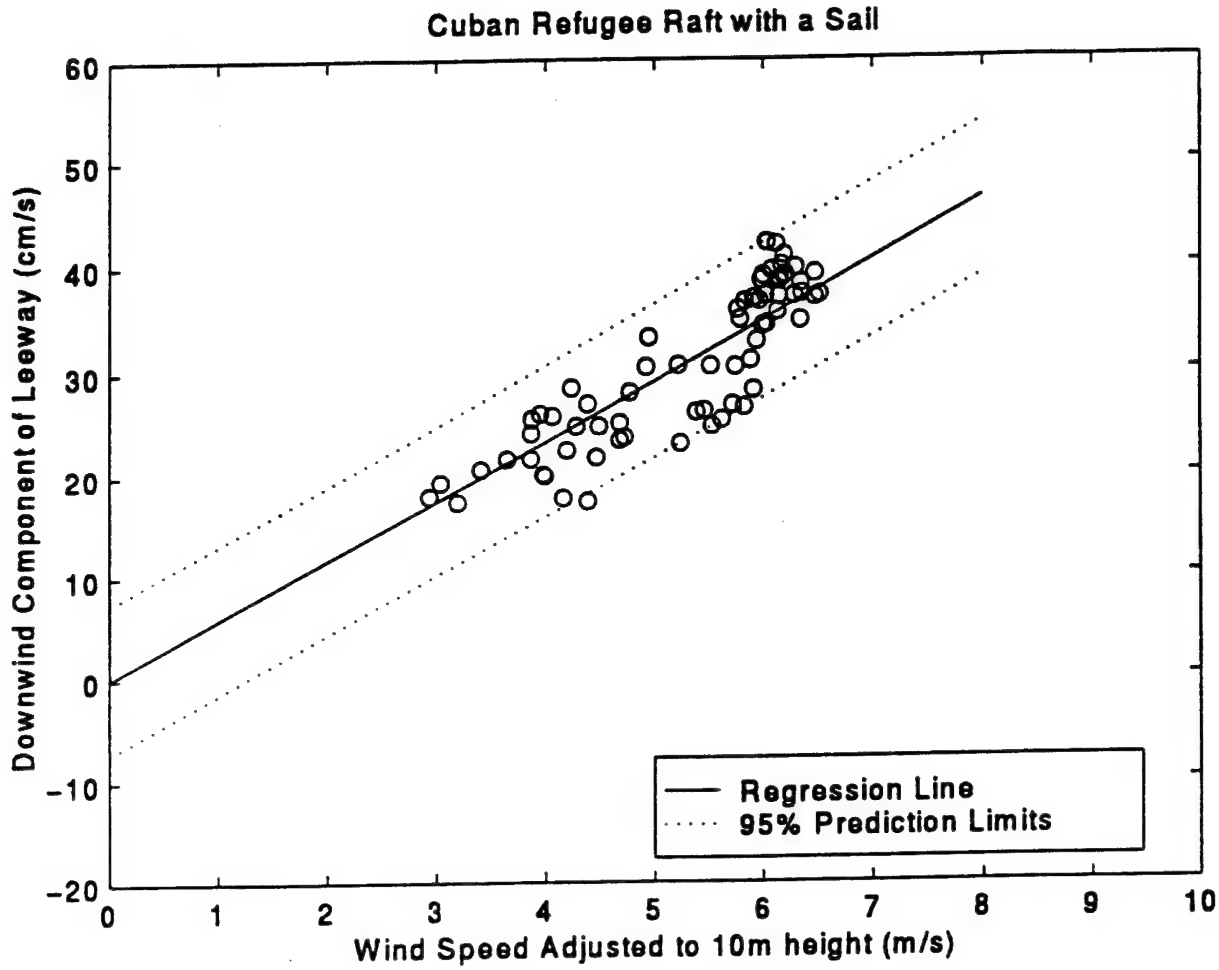


Figure 4-13. The Constrained Regression of the Downwind Component of Leeway versus Wind Speed at 10m, Cuban Refugee Raft w/ Sail.

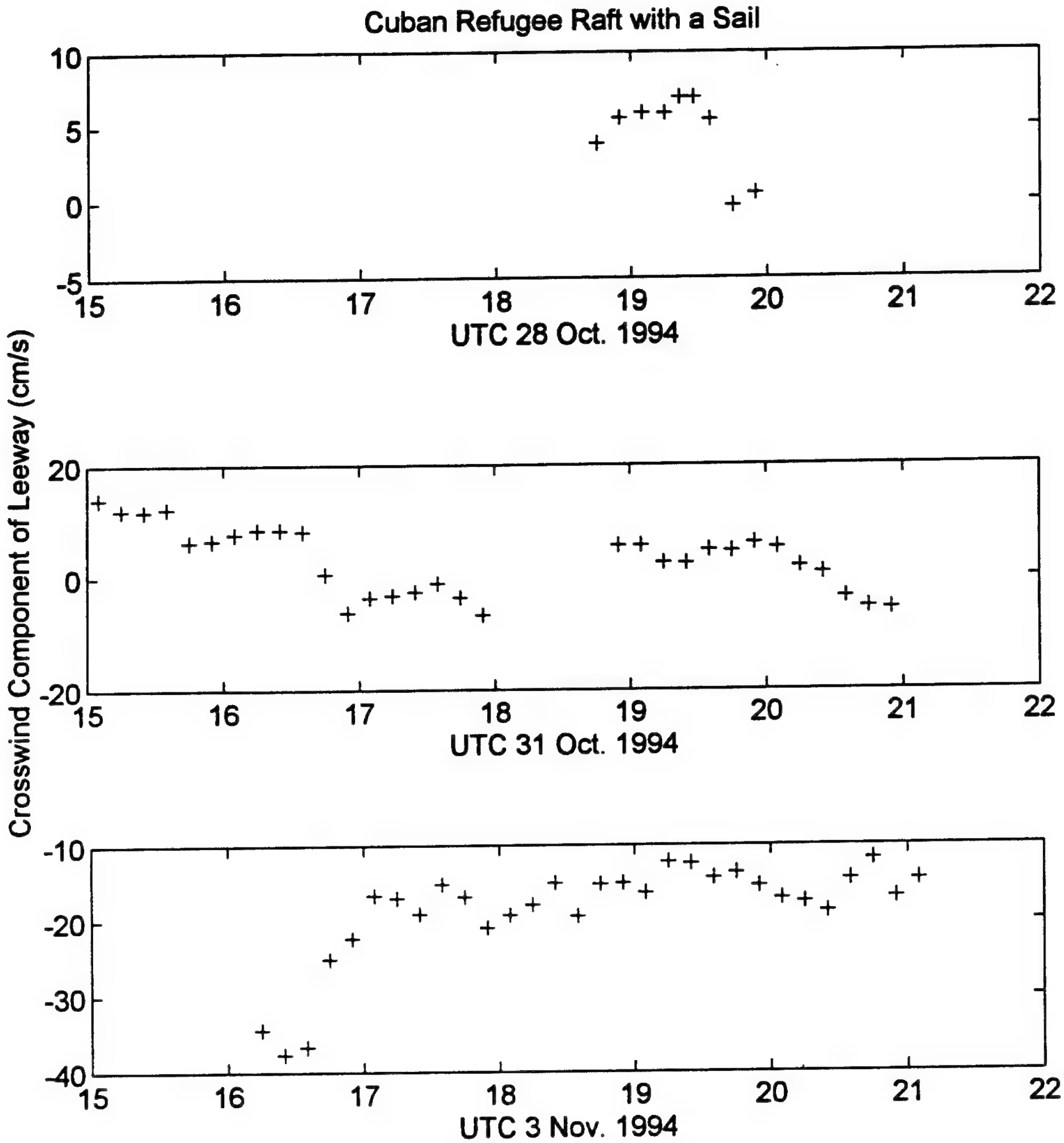


Figure 4-14. Crosswind Components of Leeway time series, Cuban Refugee Raft w/ Sail

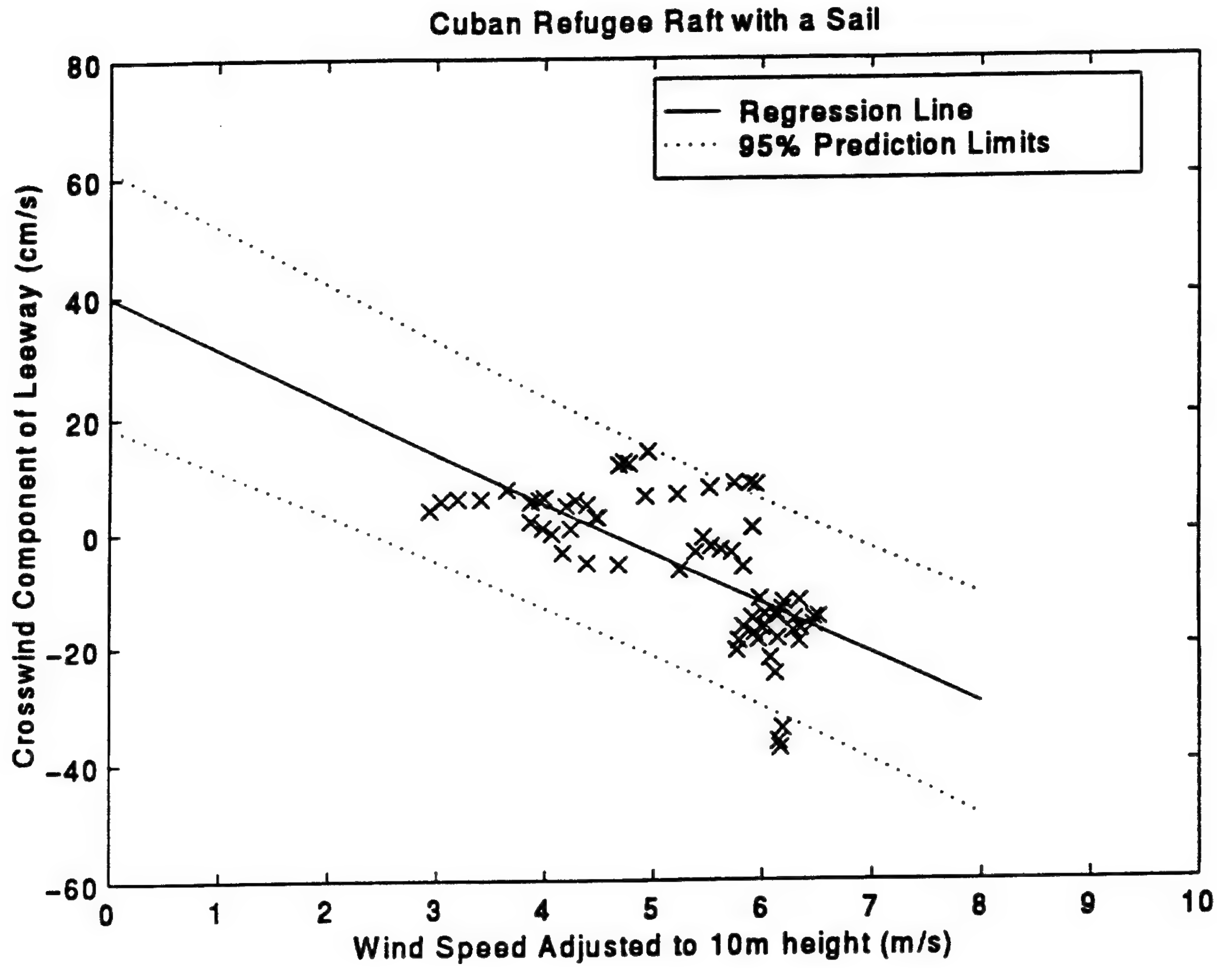


Figure 4-15. The Linear Regression of the Crosswind Component of Leeway versus Wind Speed at 10m, Cuban Refugee Raft w/ Sail.

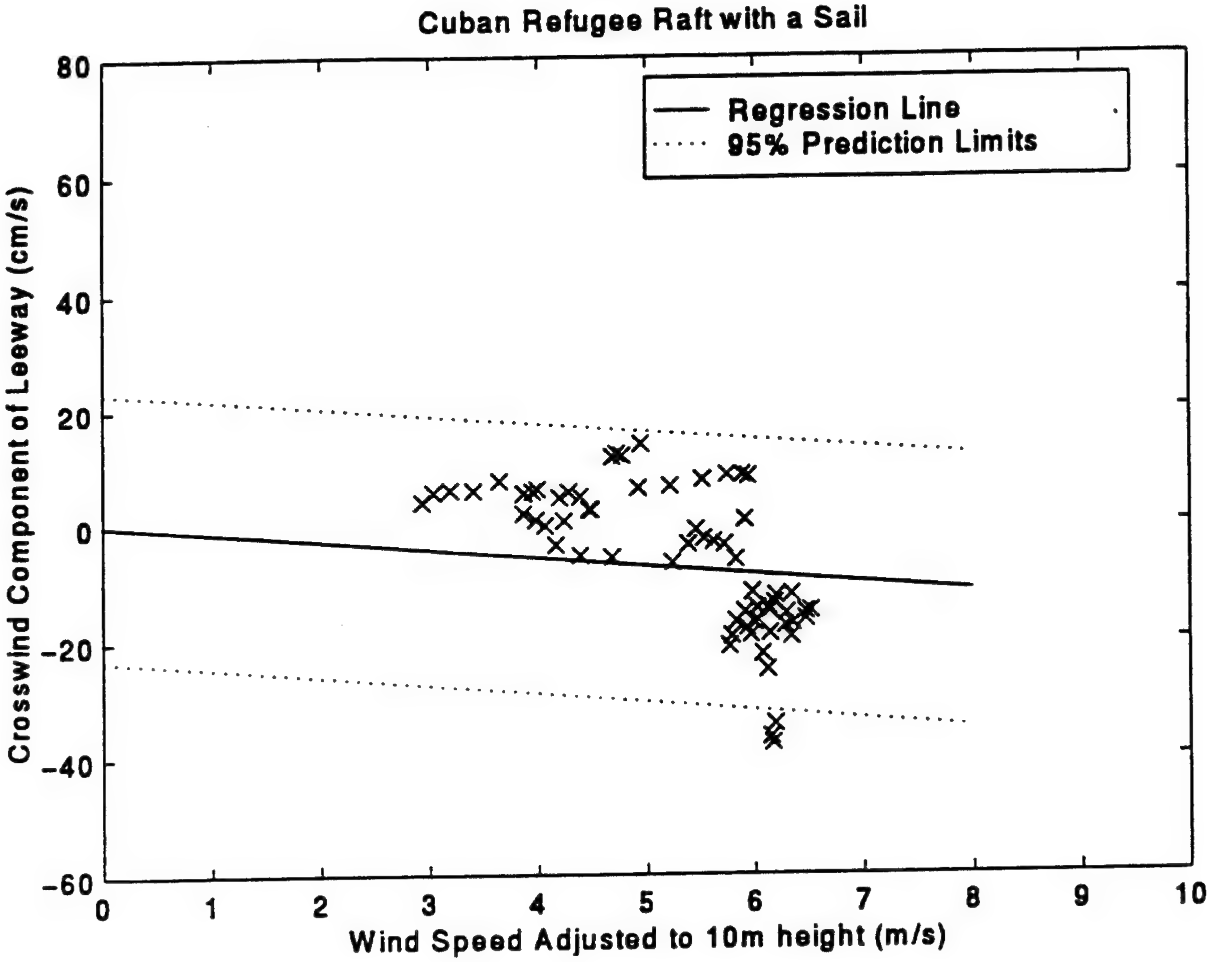


Figure 4-16. The Constrained Regression of the Crosswind Component of Leeway versus Wind Speed at 10m, Cuban Refugee Raft w/ Sail.

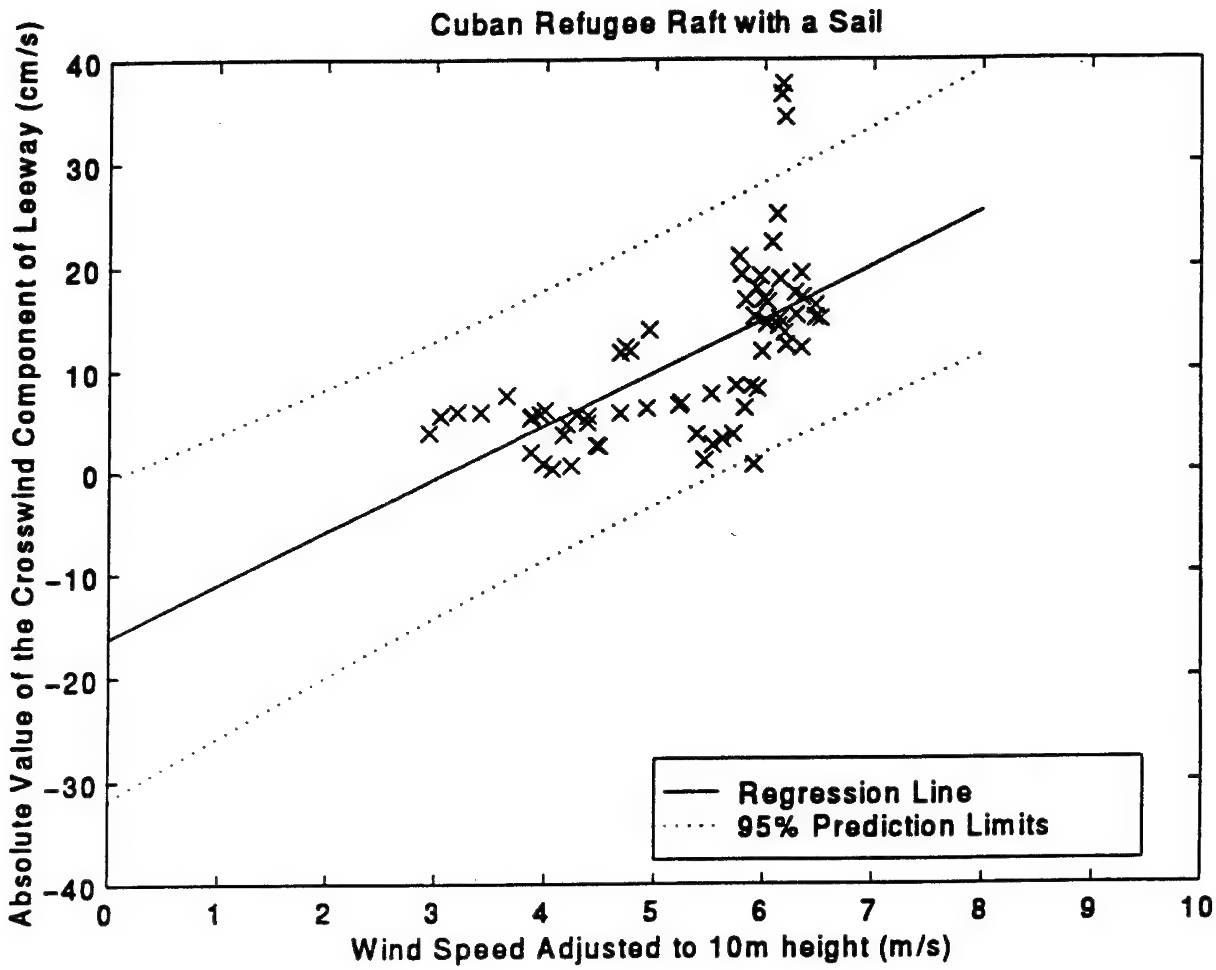


Figure 4-17. The Linear Regression of the Absolute Value of the Crosswind Component of Leeway versus Wind Speed at 10m, Cuban Refugee Raft w/ Sail.

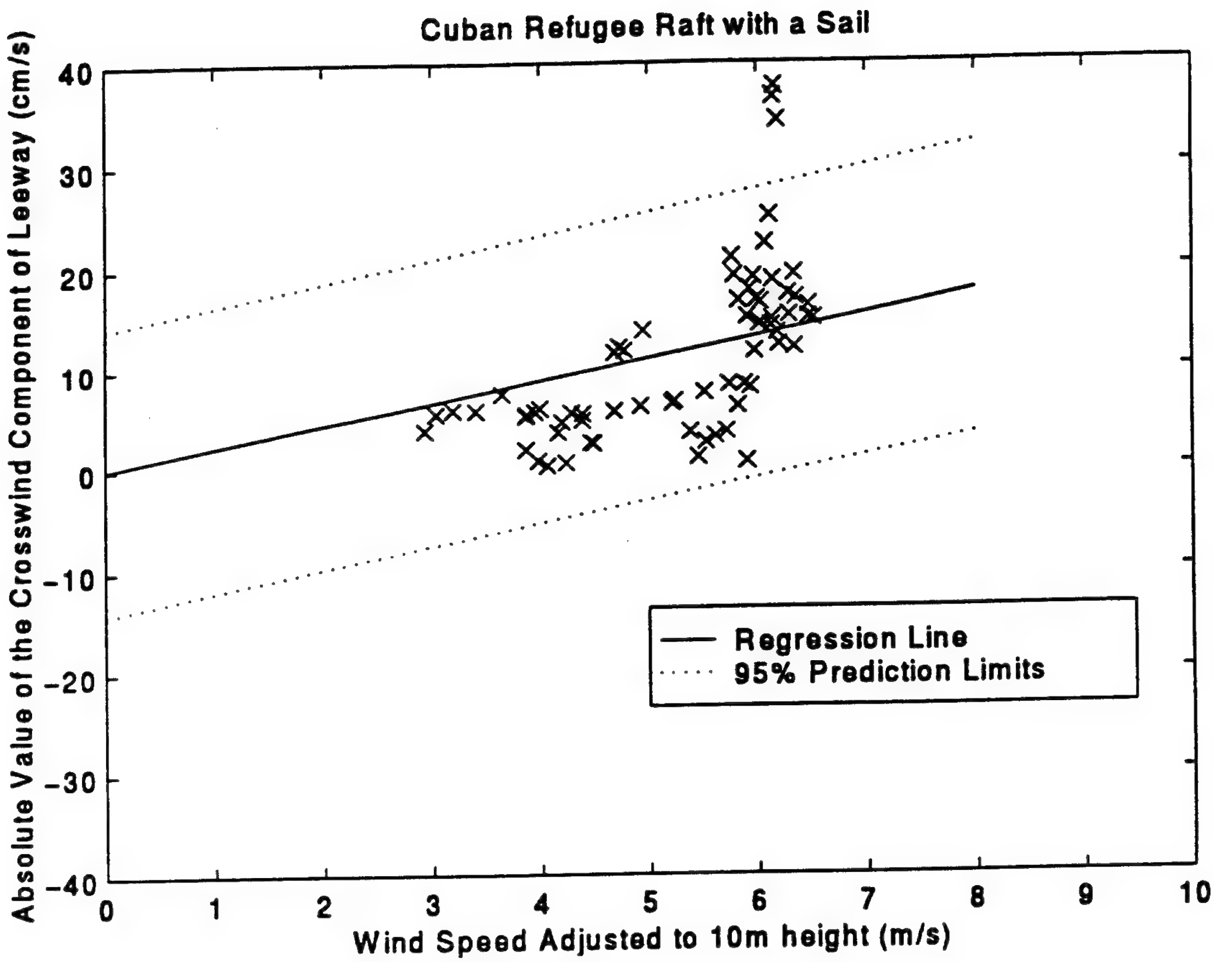


Figure 4-18. The Constrained Regression of the Absolute Value of the Crosswind Component of Leeway versus Wind Speed at 10m, Cuban Refugee Raft w/ Sail.

4.4 COMMERCIAL FISHING VESSEL WITH REAR-REEL FOR NET FISHING

The commercial fishing vessel LITTLE GLEN was used to collect 177 ten minute leeway averages collected over 13 drift runs. The 10 meter wind speed ranged from 1.3 to 8.8 m/s and the wave height was measured between 0.5 and 1.3 meters. Wind data for the fishing vessel were collected by the onboard WeatherPak® wind monitoring system, except for the 25 October 1994 run. The winds from the MiniMet® buoy were used for the 25 October drift run. The fishing vessel drifted past the MiniMet® buoy, remaining within 2.8 km of the buoy. For all other runs, GPS record of the actual motion was used to correct the apparent wind velocities to true wind velocities, except for the 26 October run, when the GPS data logger failed.

The Relative Wind Direction of the fishing vessel for the drift runs on 26 October through 3 November 1994 are shown in Figure 4-19. Without the WeatherPak® system installed on 25 October 1994, there were no relative wind direction data for that drift run. During the 25 October drift run, the fishing vessel drifted with the wind on the port side. For all subsequent runs, the WeatherPak® was installed on the starboard side of the wheel house, and the fishing vessel was intentionally set drifting with the wind on the starboard side. This was done to provide the cleanest air flow to the anemometer. In Figure 4-19 there are two points that occurred at the beginning of the drift runs where the relative wind direction was on the port side. The mean relative wind direction was 109° $\pm$ 15° standard deviation, with a range 86° to 174°.

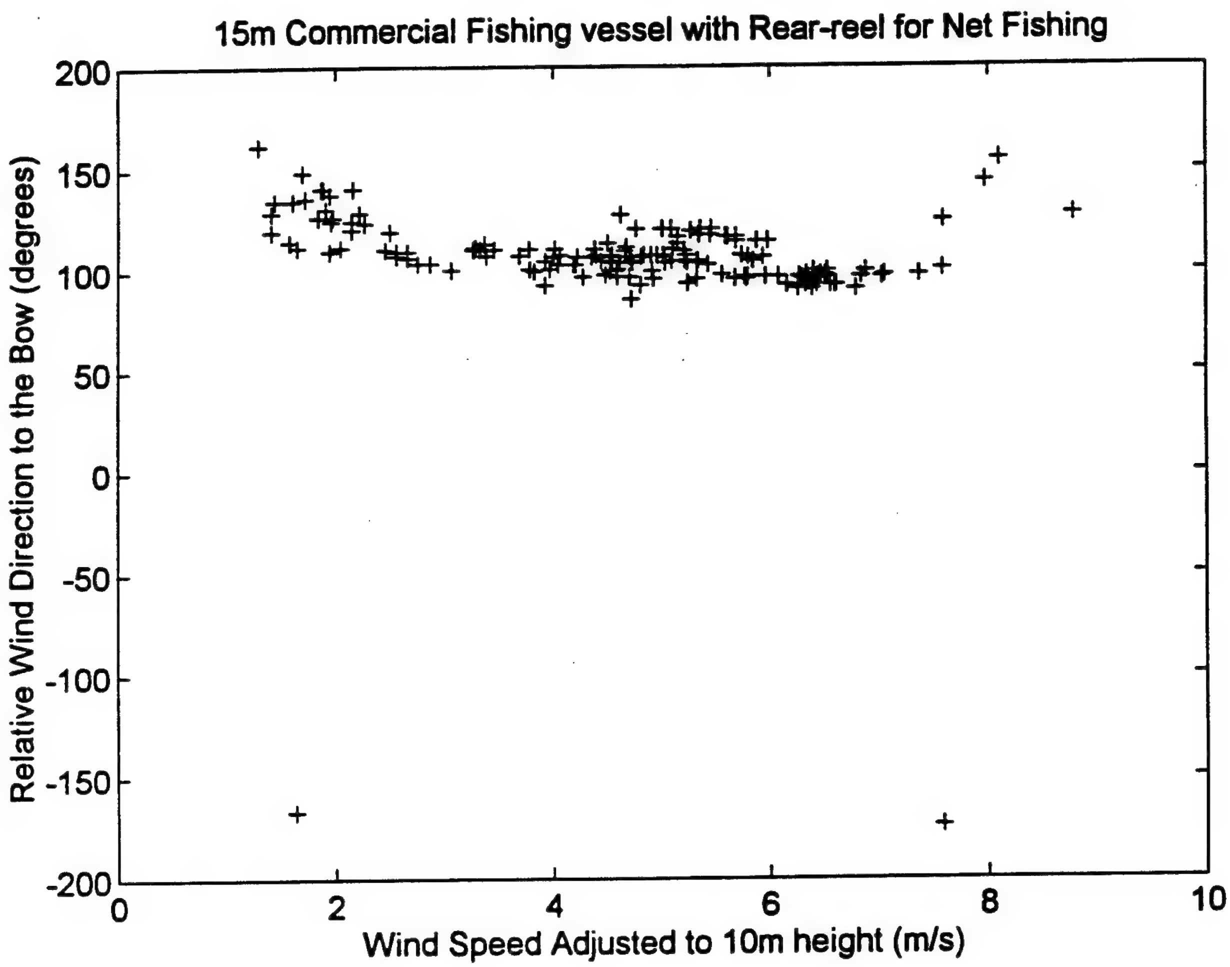


Figure 4-19. Relative Wind Direction versus Wind Speed at 10m, 15m Commercial Fishing Vessel with Rear-reel for Net Fishing

4.4.1 Leeway Angle, Rate and Speed

The leeway angle of the fishing vessel shows considerable scatter below wind speeds of 2 m/s (Figure 4-20). The cluster of positive leeway angles (centered at +40°, 6 m/s) are all from the 25 October drift run, when the vessel was port side to the wind. Most of the leeway angles were negative when the vessel had the wind on the starboard side. Leeway angle ranged from -64° to +118°, with a mean of -21.6° ± 23.5° standard deviation. The mean absolute values for leeway angle was 29.0° ± 13.4° standard deviation.

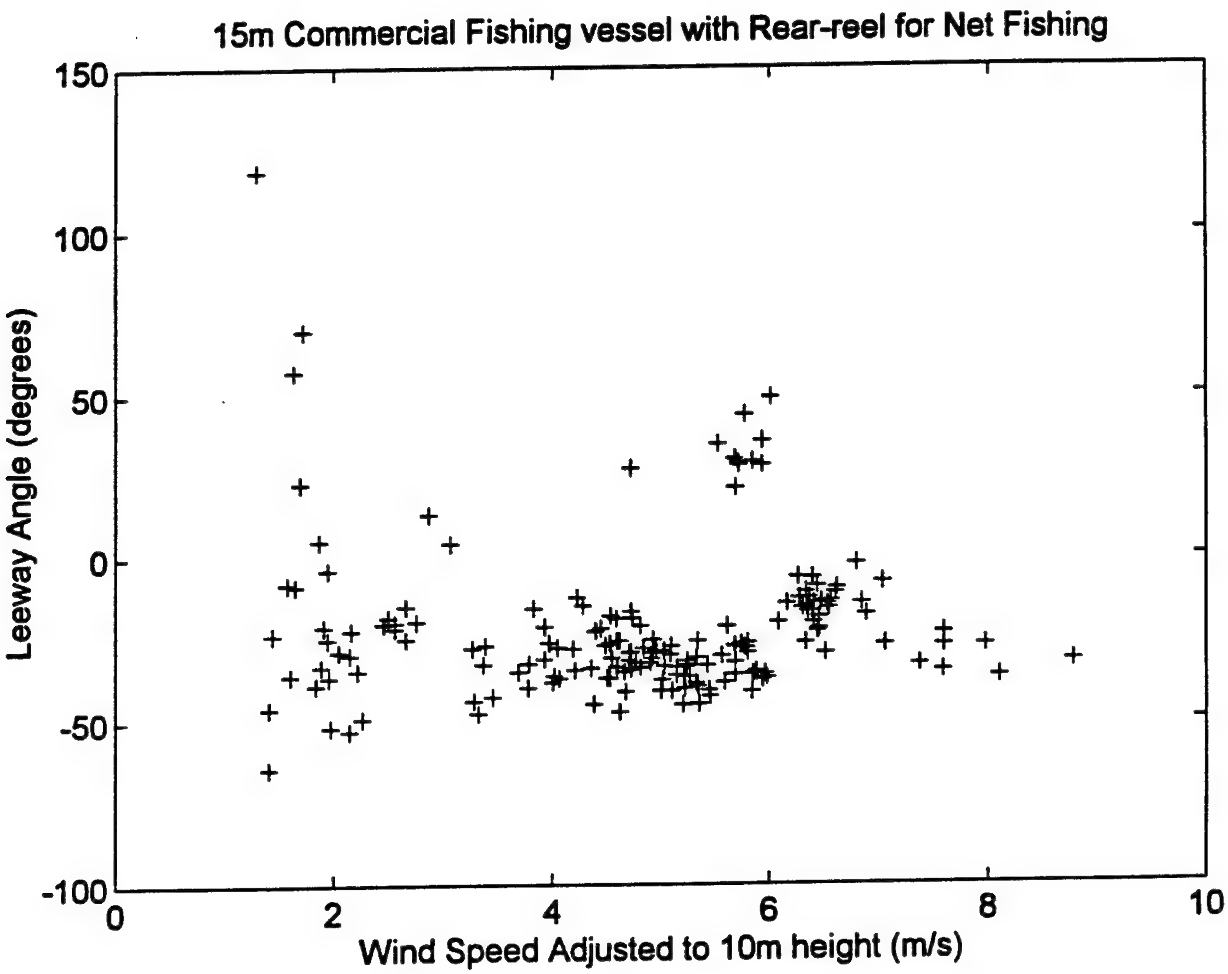


Figure 4-20. Leeway Angle versus Wind Speed at 10m, 15m Commercial Fishing Vessel with Rear-reel for Net Fishing

The mean leeway rate for the fishing vessel was 4.05% ± 0.713%, with a range of 0.50% to 5.54%. The low leeway rates occurred at low wind speeds and at the beginning of drift runs.

The leeway speed of the fishing vessel for wind speeds adjusted to 10 meter height is shown in Figures 4-21 and 4-22. The linear and constrained regression lines along with the 95% prediction limits of leeway speed on wind speed are also shown. Linear regression is summarized in Table 4-13 and the constrained regression is summarized in Table 4-14. The two regressions are virtually the same, with a zero intercept and slope of 4.0 percent.

Table 4-13

Linear Regression of Leeway Speed (cm/s)
on 10m Wind Speed (m/s)
15m Commercial Fishing Vessel with Rear-reel for Net Fishing

Dependent Variable	#	a	b	r^2	$S_{y/x}$	W_{10m} (m/s)
Leeway Speed	177	0.31	3.98	0.823	3.00	1.3 - 8.8

Table 4-14

Constrained Regression of Leeway Speed (cm/s)
on 10m Wind Speed (m/s)
15m Commercial Fishing Vessel with Rear-reel for Net Fishing

Dependent Variable	#	a	b	r^2	$S_{y/x}$	W_{10m} (m/s)
Leeway Speed	177	0.00	4.04	0.823	2.99	1.3 - 8.8

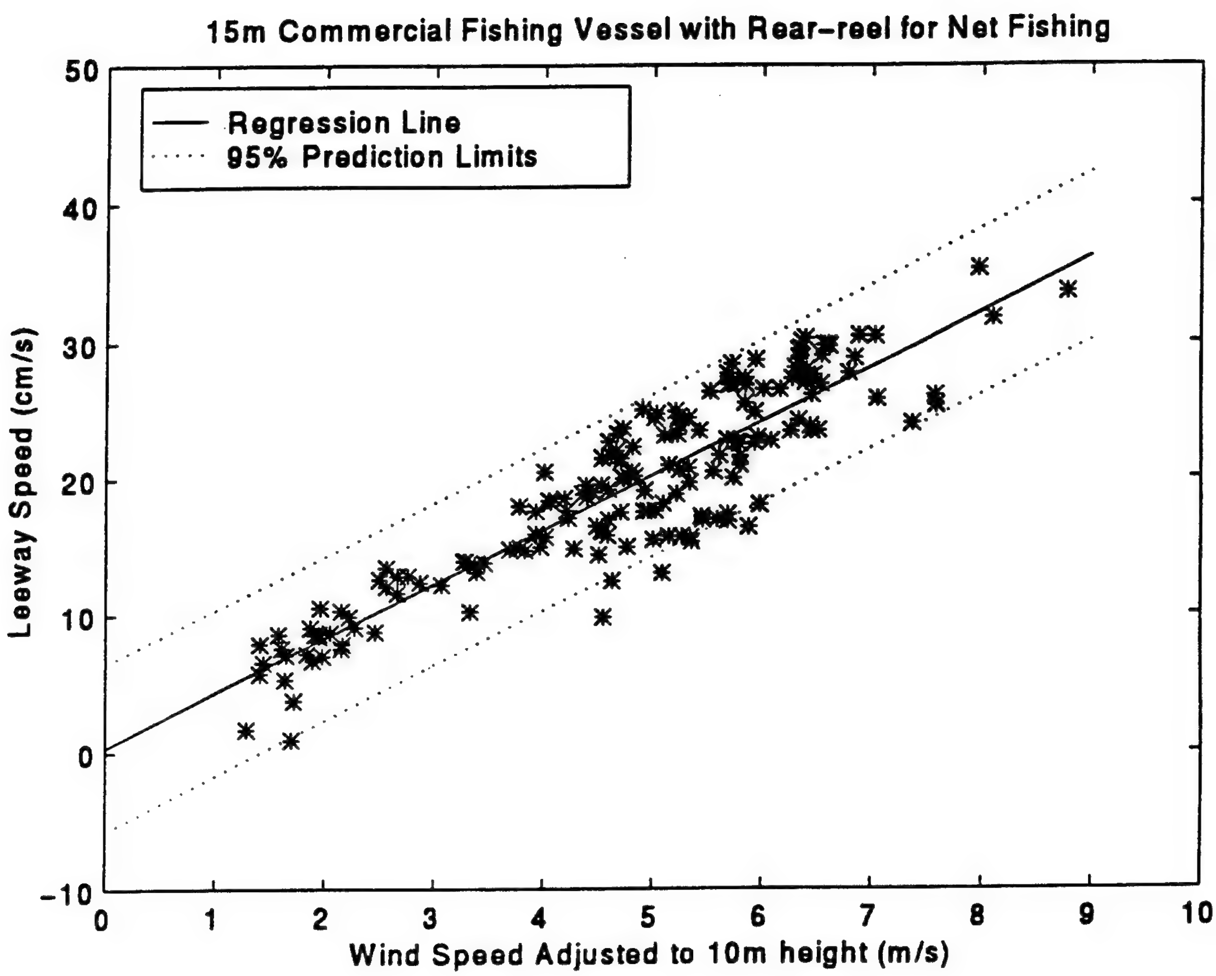


Figure 4-21. The Linear Regression of Leeway Speed versus Wind Speed at 10m, 15m Commercial Fishing Vessel with Rear-reel for Net Fishing

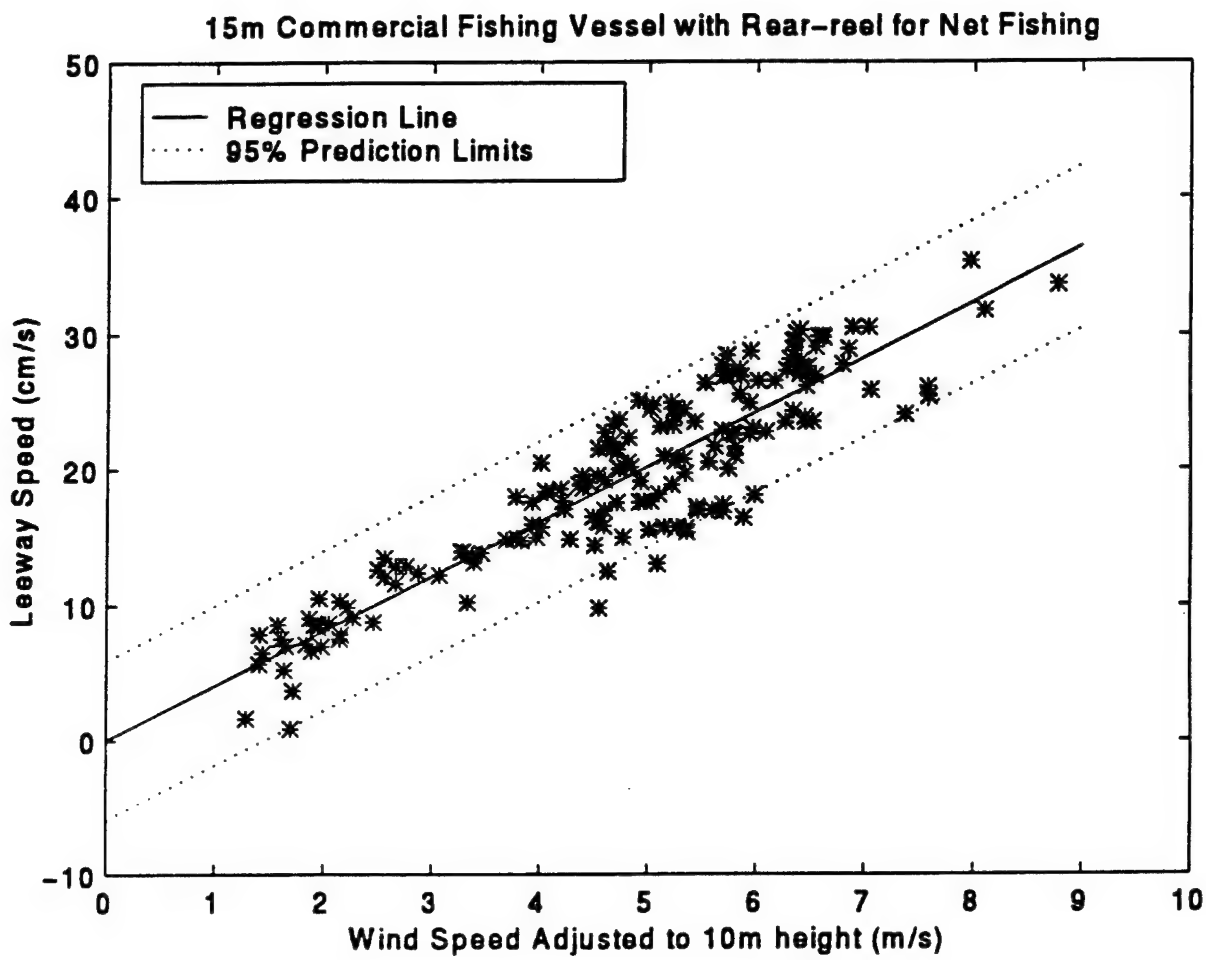


Figure 4-22. The Constrained Regression of Leeway Speed versus Wind Speed at 10m, 15m Commercial Fishing Vessel with Rear-reel for Net Fishing

4.4.2 Downwind and Crosswind Leeway Components

The downwind component of leeway for the fishing vessel is shown in Figures 4-23 and 4-24. The linear and the constrained regression lines along with the 95% prediction limits are also shown.

The crosswind component of leeway is presented in Figures 4-25 and 4-26. The linear and constrained regression lines along with the 95% prediction limits for the crosswind leeway components on 10 meter wind speed are also shown. Because there were positive and negative crosswind components, both linear and constrained regression line were also fitted to the absolute values of the crosswind component, and are presented in Figures 4-27 and 4-28. Linear regression of the two leeway components are summarized in Table 4-15 and the constrained regression are summarized in Table 4-16.

Table 4-15
Linear Regression of Leeway Components (cm/s)
on 10m Wind Speed (m/s)
15m Commercial Fishing Vessel with Rear-reel for Net Fishing

Dependent Var	#	a	b	r^2	$S_{y/x}$	W_{10m} (m/s)
DWL	177	-0.87	3.72	0.767	3.33	1.3 - 8.8
CWL	177	-2.31	-0.95	0.052	6.59	1.3 - 8.8
Abs(**CWL**)	177	2.00	1.41	0.317	3.36	1.3 - 8.8
-(Abs(**CWL**))	177	-2.00	-1.41	0.317	3.36	1.3 - 8.8

Table 4-16

Constrained Regression of Leeway Components (cm/s)
on 10m Wind Speed (m/s)
15m Commercial Fishing Vessel with Rear-reel for Net Fishing

Dependent Var	#	a	b	r^2	$S_{y/x}$	W_{10m} (m/s)
DWL	177	0.00	3.55	0.766	3.35	1.3 - 8.8
CWL	177	0.00	-1.38	0.040	6.64	1.3 - 8.8
Abs(CWL)	177	0.00	1.78	0.292	3.43	1.3 - 8.8
-Abs(CWL))	177	0.00	-1.78	0.292	3.43	1.3 - 8.8

The wind was on the port side of the fishing vessel only during the 25 October drift run. The other 12 runs were all conducted intentionally with wind on the starboard side of the vessel. The crosswind component of leeway was positive when the vessel was on the port side and generally negative (left of the downwind direction) when the wind was on the starboard side. It was assumed if data had been collected equally on both tacks, that the crosswind components would have been approximately symmetrical about the downwind direction. The regressions were conducted on the absolute value of the crosswind component. The regression lines shown are for both plus and minus absolute values of crosswind components on the 10 meter wind speed.

The 95% prediction limits were calculated following the procedure described in section 3.3.3.2. The coefficients to Equation 3-10 for the upper and lower 95% prediction limits are presented in Table 4-17 and Table 4-18. The application of these coefficients in equation 3-10 is illustrated in Chapter 5.

Table 4-17

The Coefficients of the Polynomials Describing
95% Prediction Limits of the
Linear Regression of Leeway Components (cm/s)
on 10m Wind Speed (m/s)
15m Commercial Fishing Vessel with Rear-reel for Net Fishing

Dependent Variable	Upper limits			Lower Limits		
	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3
DWL	0.0070	5.8787	3.6507	-0.0070	3.3737	-7.6245
CWL	0.0138	-1.0782	11.0429	-0.0138	-0.8150	-15.662
Abs. (**CWL**)	0.0070	1.3380	8.7976	-0.0070	1.4721	-4.8039
-Abs. (**CWL**)	0.0070	-1.4721	4.8039	-0.0070	-1.3380	-8.7976

Table 4-18

The Coefficients of the Polynomials Describing
95% Prediction Limits of the
Constrained Regression of Leeway Components (cm/s)
on 10m Wind Speed (m/s)
15m Commercial Fishing Vessel with Rear-reel for Net Fishing

Dependent Variable	Upper limits			Lower Limits		
	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3
DWL	0.0007	3.5529	6.5790	-0.0007	3.5528	-6.5790
CWL	0.0014	-1.3816	13.0478	-0.0014	-1.3818	-13.048
Abs. (**CWL**)	0.0007	1.7813	6.7247	-0.0007	1.7812	-6.7247
-Abs. (**CWL**)	0.0007	-1.7813	6.7247	-0.0007	-1.7813	-6.7247

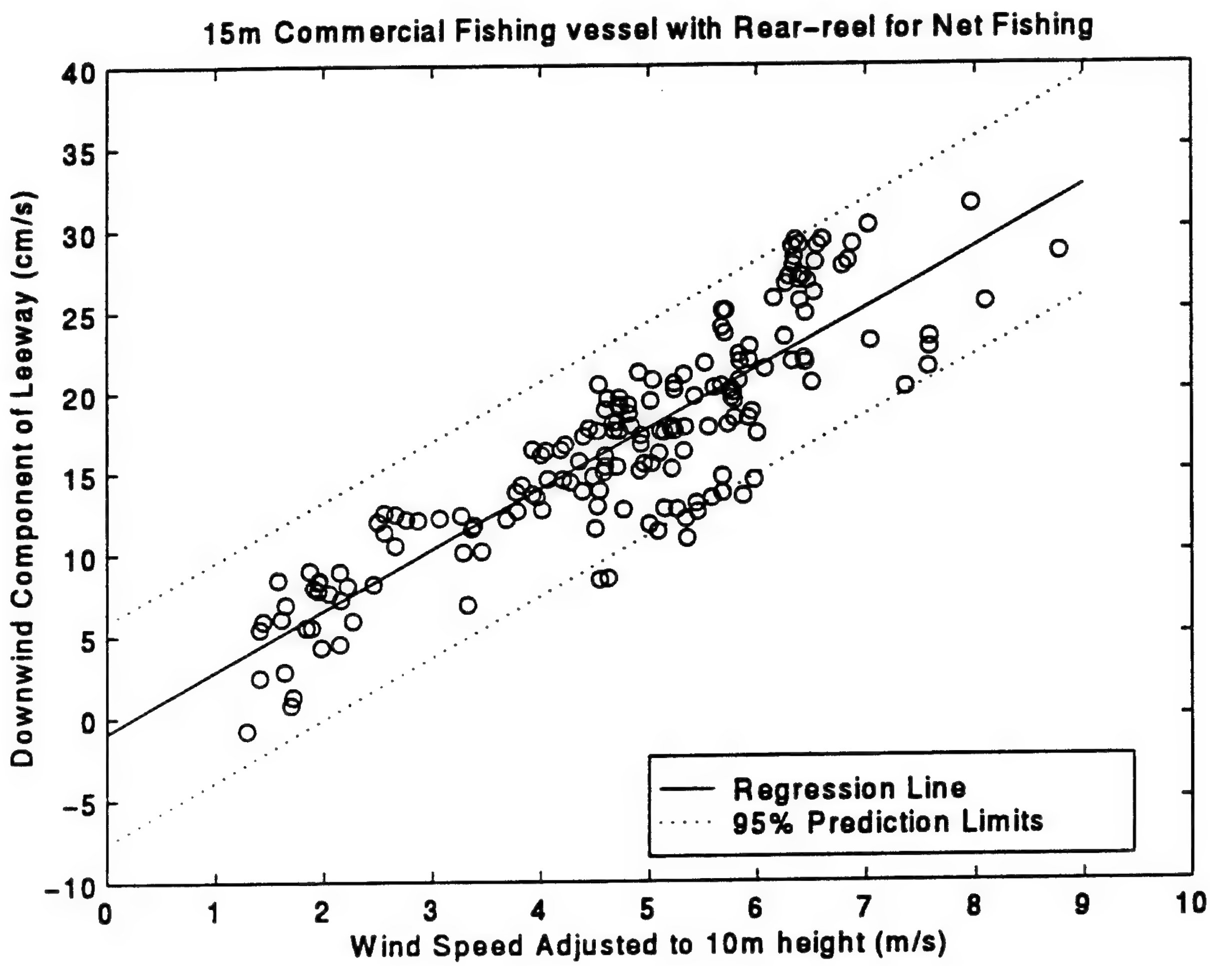


Figure 4-23. The Linear Regression of the Downwind Component of Leeway versus Wind Speed at 10m, 15m Commercial Fishing Vessel with Rear-reel for Net Fishing.

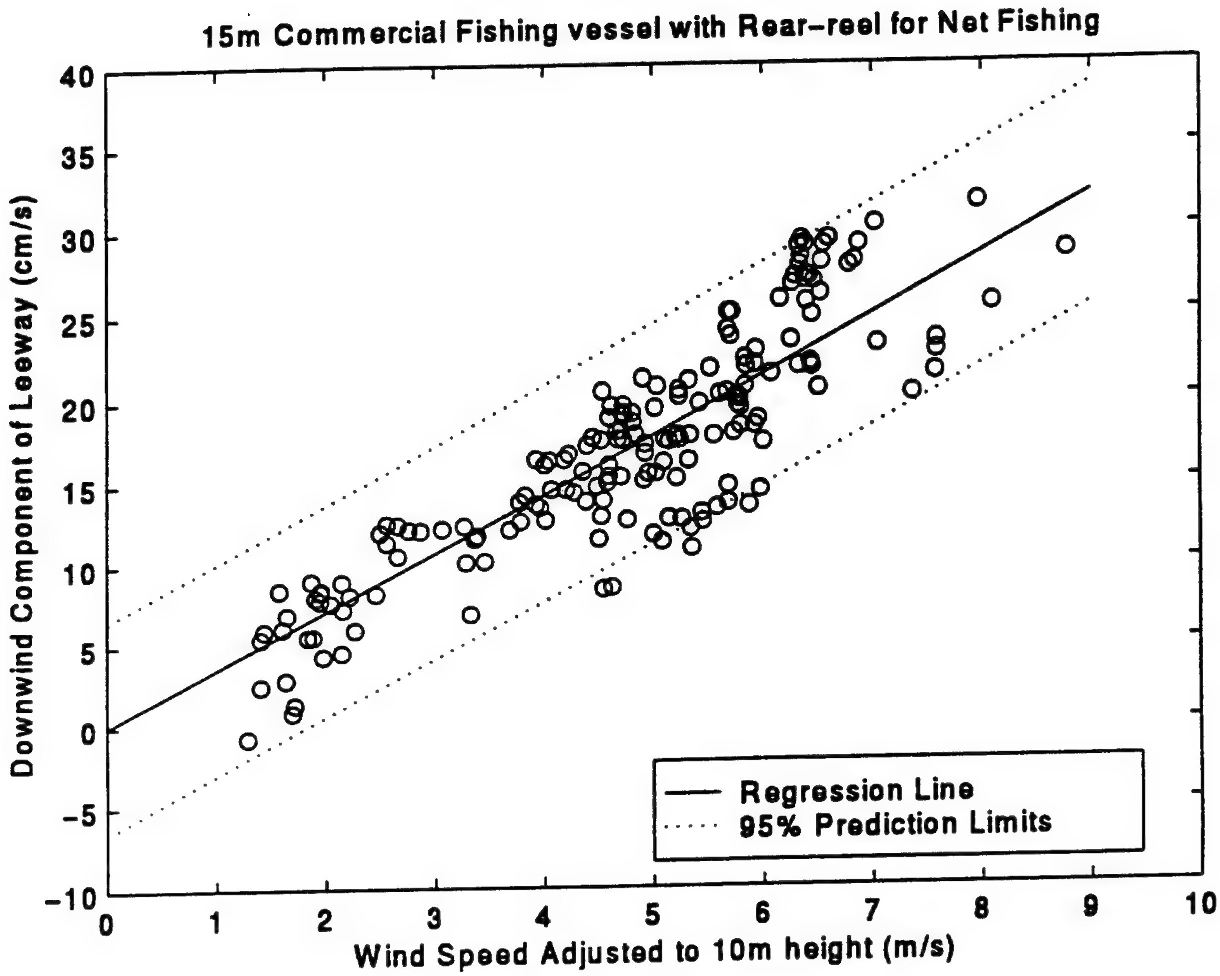


Figure 4-24. The Constrained Regression of the Downwind Component of Leeway versus Wind Speed at 10m, 15m Commercial Fishing Vessel with Rear-reel for Net Fishing.

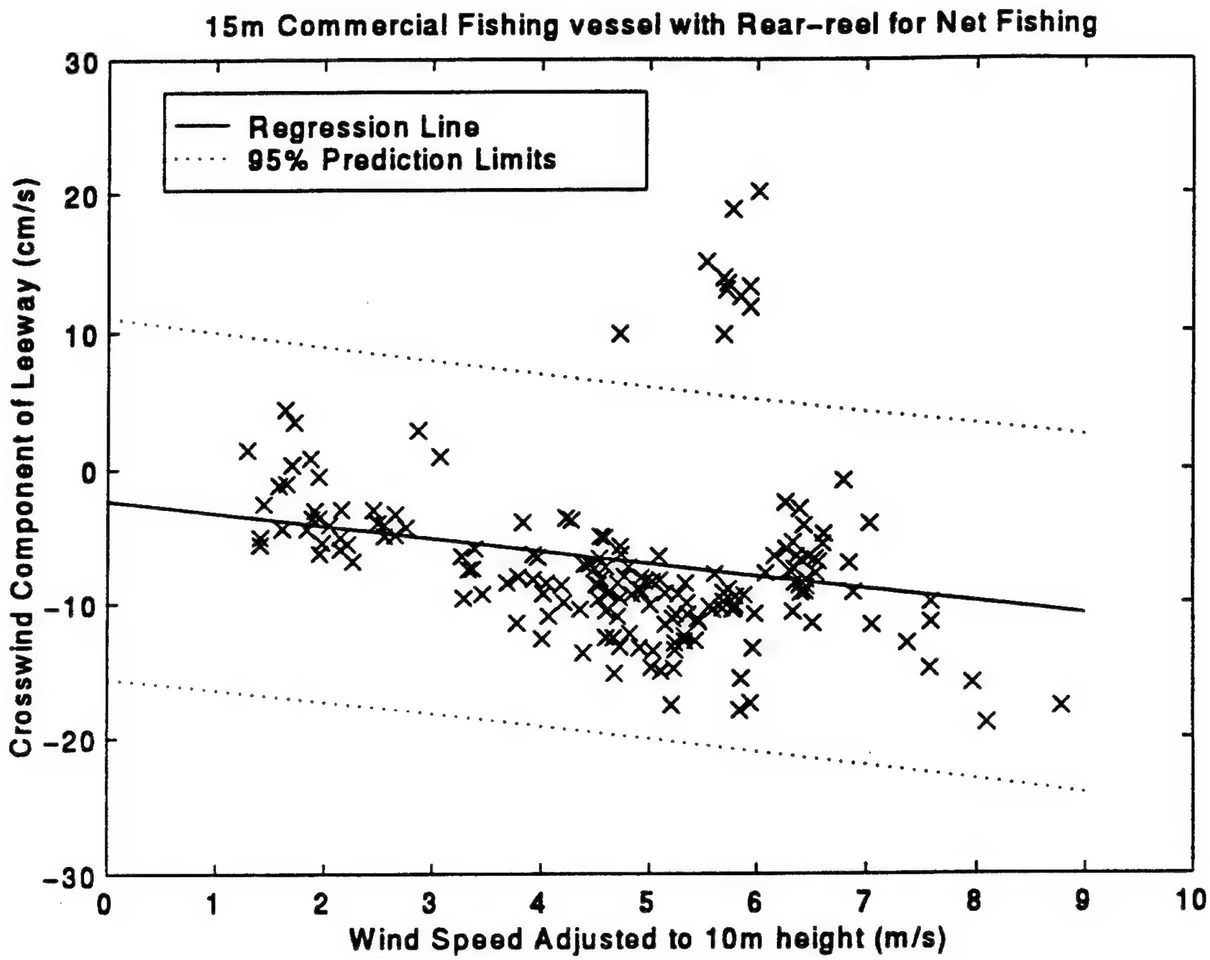


Figure 4-25. The Linear Regression of the Crosswind Component of Leeway versus Wind Speed at 10m, 15m Commercial Fishing Vessel with Rear-reel for Net Fishing.

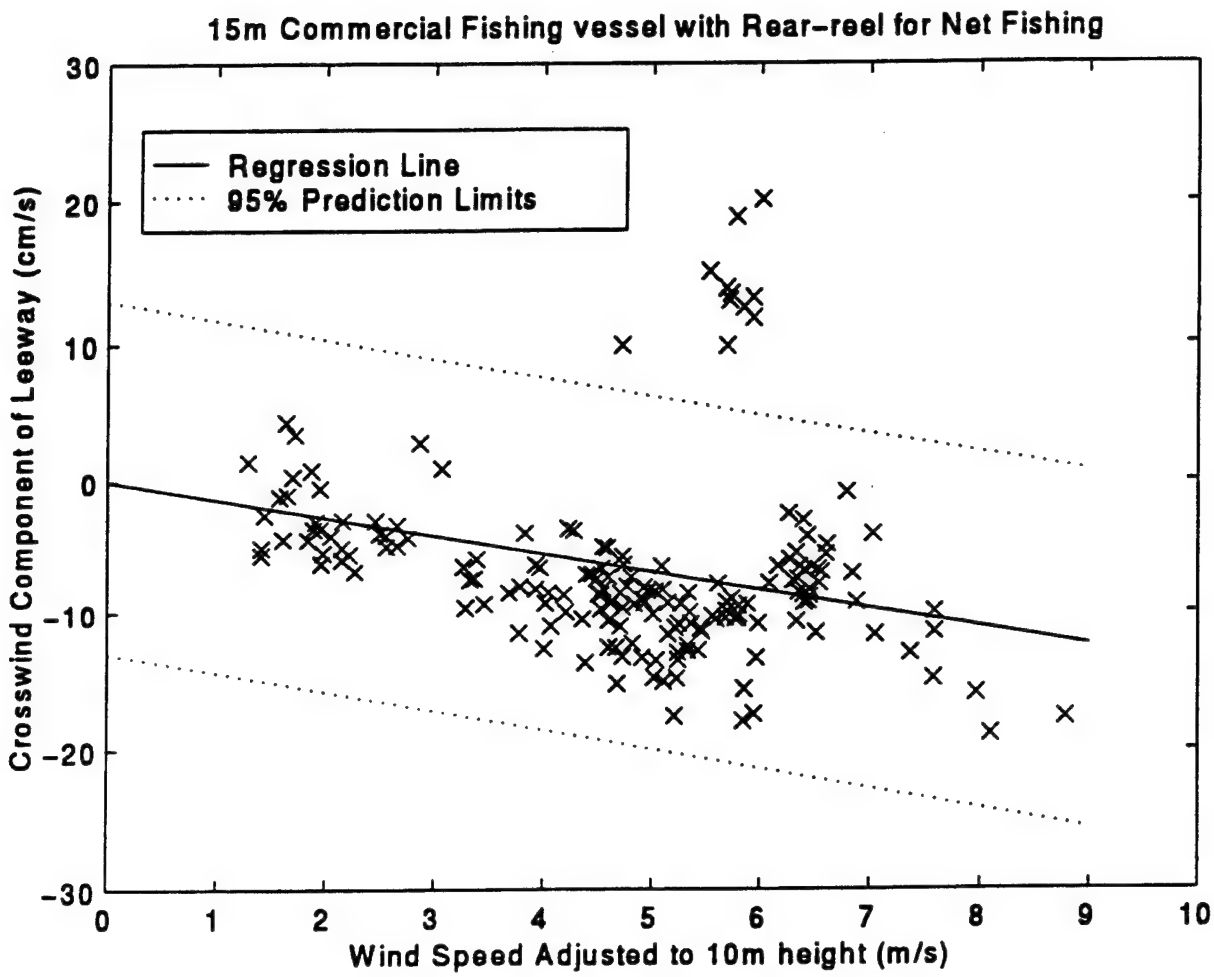


Figure 4-26. The Constrained Regression of the Crosswind Component of Leeway versus Wind Speed at 10m, 15m Commercial Fishing Vessel with Rear-reel for Net Fishing.

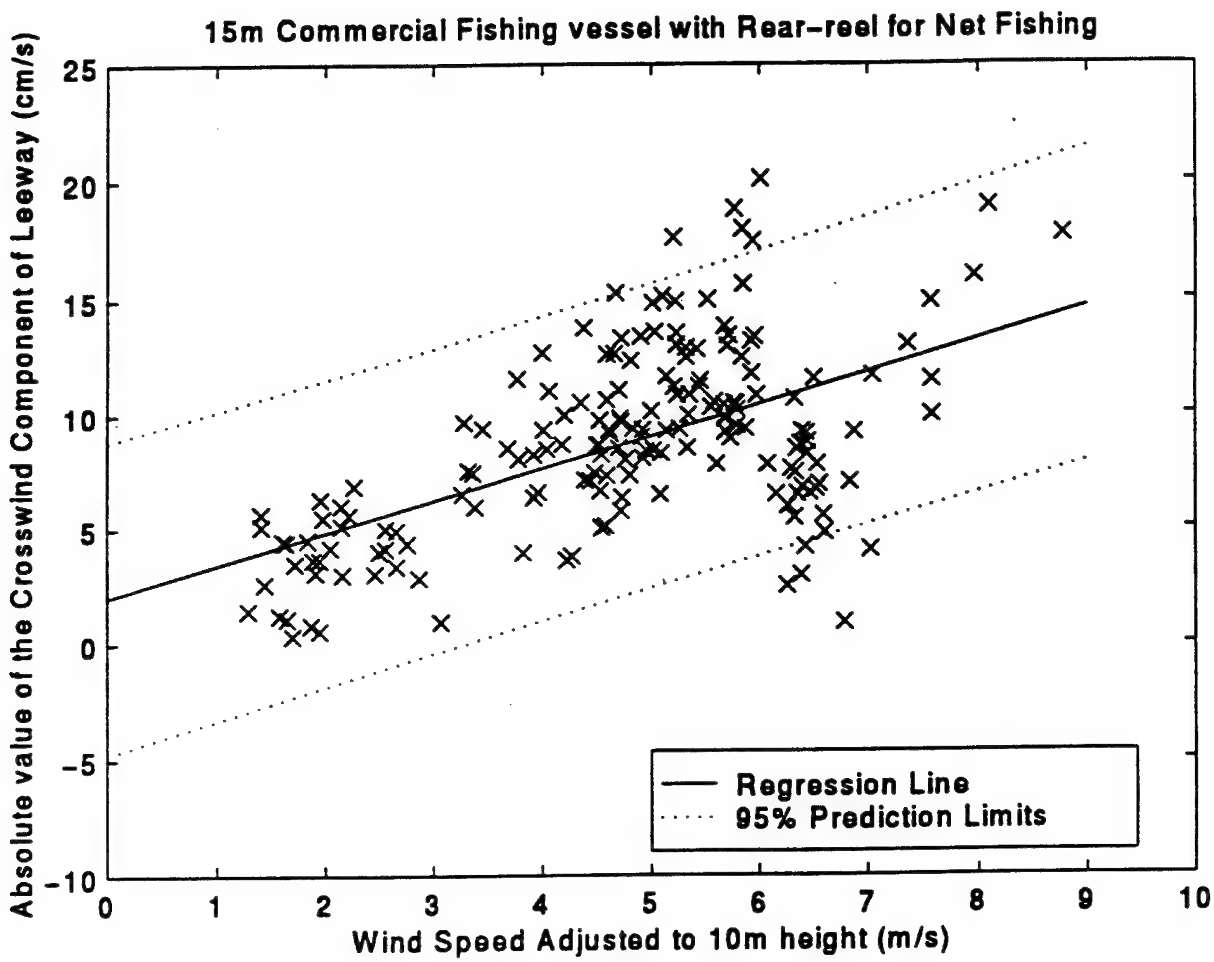


Figure 4-27. The Linear Regression of the Absolute Value of the Crosswind Component of Leeway versus Wind Speed at 10m, 15m Commercial Fishing Vessel with Rear-reel for Net Fishing.

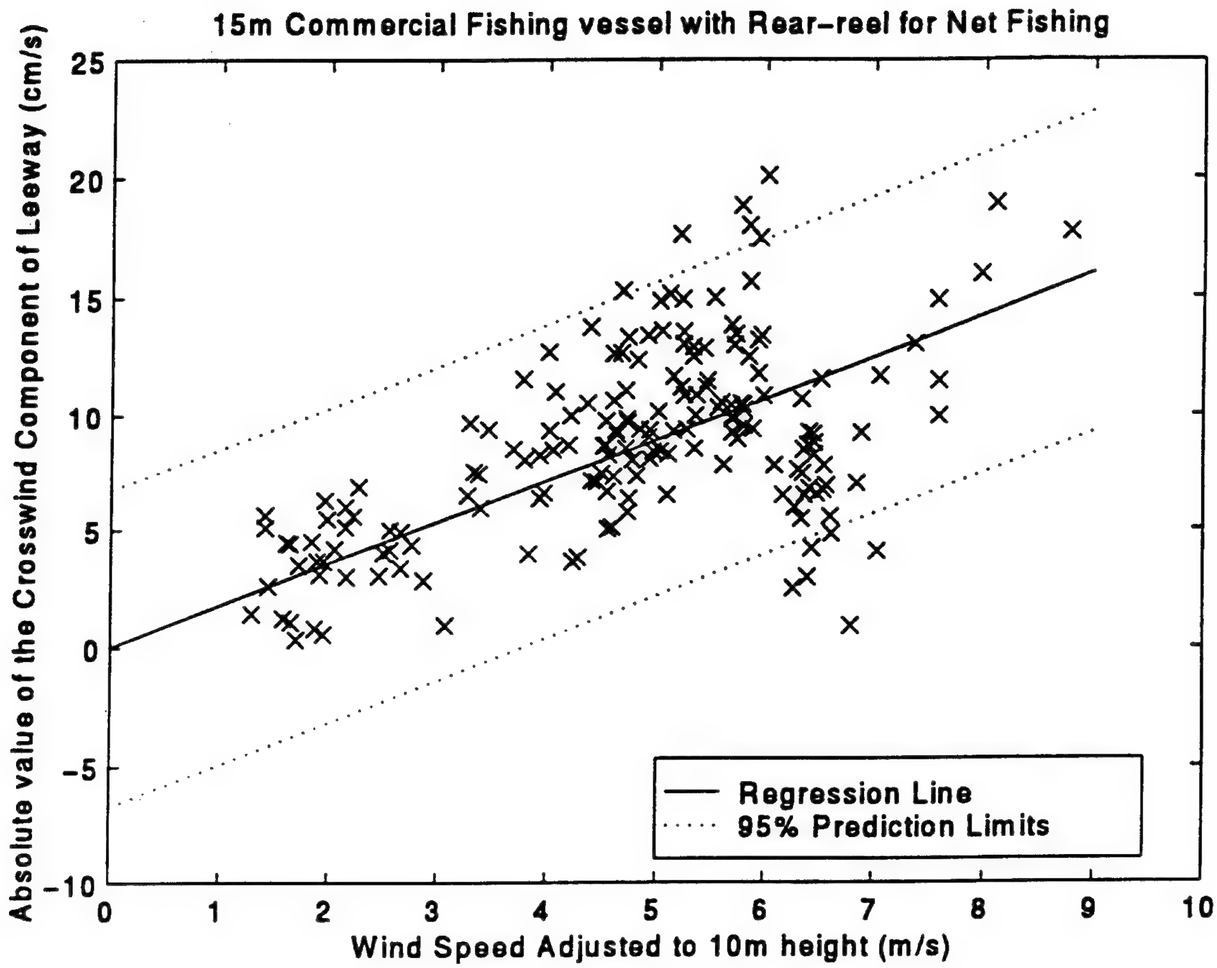


Figure 4-28. The Constrained Regression of the Absolute Value of the Crosswind Component of Leeway versus Wind Speed at 10m, 15m Commercial Fishing Vessel Rear-reel for Net Fishing.

CHAPTER 5

APPLICATION OF THE UNCERTAINTY TO THE PREDICTION OF LEEWAY

5.1 INTRODUCTION

The following section presents a technique for incorporating the uncertainty of the measured observations of leeway, from these experiments, into the uncertainty of the prediction of the leeway component of a survivor craft. The 95 percent prediction limits of the crosswind and downwind components of leeway were used to estimate the limits of the predicted leeway about the mean. This technique is illustrated by applying it to one of the drift runs of the 15 meter commercial fishing vessel.

The total displacement vectors for a given SAR target are the vector sums of the total water current vectors and the wind vector transformed by the leeway equation. Four basic uncertainties affect the uncertainty of the total displacement vector. There are uncertainties in the two force vectors: wind and total water current. There is also an uncertainty in the representation of the actual SAR target in the leeway equation relative to a tested class of targets. There is also uncertainty in the leeway equation itself for a class of targets. It is the uncertainty in the leeway equation that is addressed here.

For this illustration, only the leeway portion of the total displacement is included. Since the predicted leeway can be compared directly to the observed leeway, the uncertainty of the total water current can be separated and need not be considered. Winds were measured at the leeway target, therefore, wind uncertainty is considered to be zero. The actual SAR target, the 15 meter commercial fishing vessel, is the same vessel used in determining the leeway equation. Therefore, there was no uncertainty in whether the target leeway was represented by the leeway equation. Thus the only uncertainty is in the leeway equation itself and variability of the actual leeway target drift.

5.1.1. Background

The uncertainty in the predicted displacement of a survivor craft by CASP (versions 1.0 and 1.1a) has been handled by using the Monte Carlo technique. The Monte Carlo technique uses many replications (1000's) and builds a probability distribution from the results. Raunig, Robe, and Perkins (1995) describe how CASP handles the spreading of the search area from the initial probability distribution. For a leeway target, the leeway angle is randomly selected between the maximum left and right leeway angles for that

target. Leeway speed is a discrete value for each wind speed for each target type. There is no distribution about the leeway speed. Originally the leeway angle was reselected every time step (6 hours), which results in the center of the probability distribution converging to the mean downwind angle of zero. In the most recent version of CASP, 1.1b, the leeway distribution is a uniform distribution between the left and right values of the leeway angle, chosen only once at the beginning of each replication. For wind, CASP version 1.1b uses a circular normal distribution with a standard deviation of 5 knots about the mean downwind vector. The final drift distribution of leeway and wind is a combination of the two distributions centered on the mean downwind vector, (Raunig, Robe, and Perkins (1995), Figure 2-7a).

In the CANadian Search And Rescue Prediction program (CANSARP), which does not use the Monte Carlo technique, leeway is handled by using the minimum and maximum leeway angles and speeds for the SAR target. Because the limits for leeway angles are large compared to the limits of the leeway speed, CANSARP tends to produce an arc distribution pattern centered on the downwind direction.

If the mean crosswind and downwind component of leeway equations are going to be used in numerical search models, a method of incorporating the 95 percent prediction limits should be used to estimate the probability distribution.

5.2 DESCRIPTION OF AN INDIVIDUAL DRIFT RUN

The application of these results to search models is illustrated by following an example from regression equations through to an estimate of leeway and leeway uncertainty displacement. The 95% prediction limits of linear regression of the downwind and the absolute value of crosswind components of leeway on the 10 meter wind speed were used to estimate the uncertainty of the leeway displacement vector. When other variables are controlled, the mean predicted target leeway within the 95% prediction limits should agree with the observed target's leeway distribution.

5.2.1 The Observations

The second leeway drift run on 28 October 1994 of the 15 meter commercial fishing vessel was used to illustrate the relationships between winds, currents, leeway and the total displacement of the leeway target. In the progressive vector diagram (Figure 5-1) the displacement vectors are presented for observed leeway, 4.0% of the wind, surface currents, and total drift of vessel over the ground. Velocity vectors (leeway, wind, and currents) were converted to displacement vectors by multiplying by the period of their sampling intervals. This converts velocity vectors to displacement vectors.

The total displacement vector is taken directly from the GPS positions.

During this period the winds were from the southeast at 3.0 to 4.5 m/s. The wind vectors were used in Equation 3-2 with the coefficients from Table 4-14 to estimate the mean predicted leeway vector. The predicted leeway vector had zero divergence from the downwind direction. This is the same as reducing the wind vector to 4.0% of its original size. The observed leeway displacement was left of the predicted leeway vector by 20 to 40 degrees.

Surface currents during this period were southward at 24-35 cm/s. Surface currents were available from two sources (see section 2.1.4 for description). The surface currents at MiniMet® buoy were Eulerian measurements at 0.7 meter depth located 3 kilometers to the northeast of the origin. The Lagrangian CODE drifter was released at the beginning of the drift run and recovered after the drift run. Positioning of the CODE drifter only occurred at the times of deployment and recovery, 10 minutes after completion of the drift run. The position for the CODE drifter at the end time of drift run, was estimated by interpolation. The S4® EMCM at MiniMet® buoy indicated that the surface current was 24 cm/s while the CODE drifter was drifting south at 35 cm/s. The estimated Stokes drift during this period was 2.2 cm/s, which accounts for 20% of the difference between two types of surface current measurements.

Aboard the 15 meter commercial fishing vessel was a GPS data logger that stored positions at 5 minute intervals. The drift started at the origin and movement of the fishing vessel over the ground was to the south-southwest. Although, the fishing vessel was moving through the water to the northwest (the leeway displacement) the water was carrying the vessel southward (the surface currents as estimated by the CODE drifter). The total displacement as measured by GPS positions was closely approximated by the vector sum of the observed leeway and surface currents as estimated by the CODE drifter. The Eulerian surface currents at the MiniMet® buoy and observed leeway fell short of the total displacement. However, either of these combined estimates were better than using current or leeway alone to predict the total displacement.

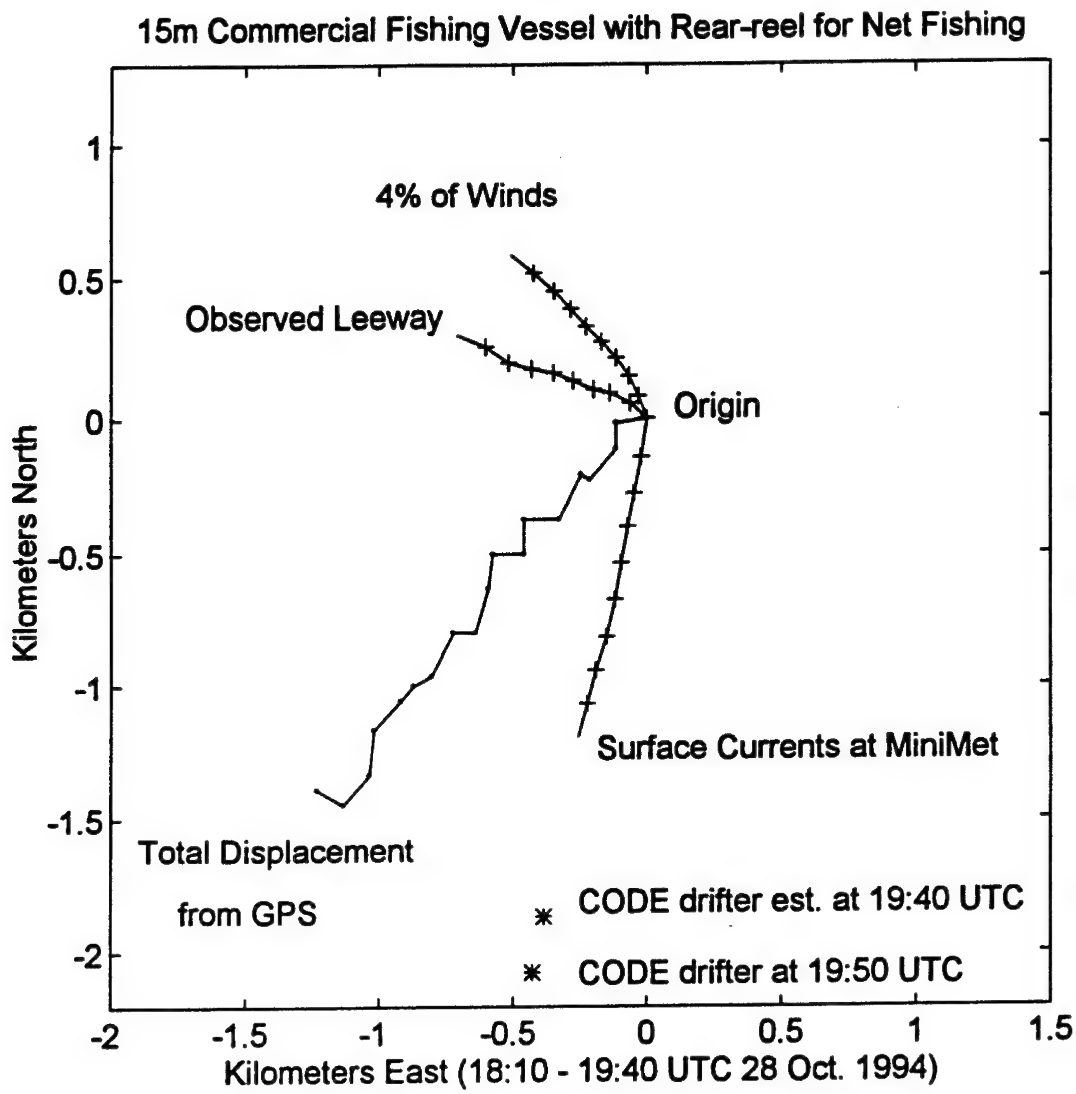


Figure 5-1. The Progressive Vector Diagram of: 4.0% of the Wind, Surface Currents at the MiniMet® buoy, Drift of a CODE drifter, Leeway and Total Displacement of a 15 m Commercial Fishing Vessel with Rear-reel for Net Fishing, for the period 18:10 -19:40 UTC 28 Oct. 1994.

5.3 PREDICTION OF THE MEAN OF THE LEEWAY DISPLACEMENT VECTOR

In Figure 5-1, the observed components of total displacement are presented. How well do the regression equations for leeway predict the observed leeway? The Leeway Equation 3-1, with (**DWL**, Pos. Abs. **CWL** and Neg. Abs. **CWL**) values from Table 4-15, was used to predict the downwind and crosswind components of leeway for the 15 meter commercial fishing vessel. In Figure 5-2, the progressive vectors for 4.0% of wind and observed leeway of 15 meter commercial fishing vessel are presented in Figure 5-1. In addition, the linear regression for downwind component of leeway was combined with plus and minus linear regression of the crosswind component of leeway.

$$\text{Downwind component} = -0.87 \text{ cm/s} + 3.72 \frac{(\text{cm/s})}{(\text{m/s})} \mathbf{W_{10m}} \tag{5-1}$$

$$\text{Pos. Crosswind component} = 2.00 \text{ cm/s} + 1.41 \frac{(\text{cm/s})}{(\text{m/s})} \mathbf{W_{10m}} \tag{5-2}$$

$$\text{Neg. Crosswind component} = -2.00 \text{ cm/s} - 1.41 \frac{(\text{cm/s})}{(\text{m/s})} \mathbf{W_{10m}} \tag{5-3}$$

The positive and negative crosswind components were vector added to the downwind component to produce two solutions for leeway. One for each of two possible tacks. Since the wind can come over either the port side or the starboard side of the vessel, the crosswind component will either be positive or negative. Equations 5-1 through 5-3 are in wind direction coordinate system (y-axis is downwind and x-axis is positive crosswind). To convert from a wind direction coordinate system to earth coordinate system (y-axis is north and x-axis is east), the following transformations were applied in degrees.

$$\theta = (90 - DownwindDirection) \quad (5\text{-}4)$$

(Degrees)

$$\text{East Leeway component (Pos)} = \mathbf{DWL} * \cos(\theta) + \mathbf{CWL}(\text{Pos}) * \sin(\theta) \quad (5\text{-}5)$$

$$\text{North Leeway component (Pos)} = \mathbf{DWL} * \sin(\theta) - \mathbf{CWL}(\text{Pos}) * \cos(\theta) \quad (5\text{-}6)$$

$$\text{East Leeway component (Neg)} = \mathbf{DWL} * \cos(\theta) + \mathbf{CWL}\ (\text{Neg}) * \sin(\theta) \quad (5\text{-}7)$$

$$\text{North Leeway component (Neg)} = \mathbf{DWL} * \sin(\theta) - \mathbf{CWL}\ (\text{Neg}) * \cos(\theta) \quad (5\text{-}8)$$

These equations convert the leeway vector from downwind and crosswind components to east and north components for positive (equation 5-5 and 5-6) and negative (5-7 and 5-8) cases.

The means of the predicted downwind and crosswind leeway velocity vectors were converted to displacement vectors and were progressive summed, (Figure 5-2). There are two solutions and therefore two predicted paths of the leeway, one to the right (positive) and one the left (negative) of the wind displacement vector. The negative estimated leeway vector from Equations 5-1 and 5-3 is just north of the observed leeway displacement vector. It should be noted that observed leeway was part of the data set used in the linear regression. Therefore, it is be expected that there would be good agreement between the observed and the predicted leeway vectors as they are not totally independent.

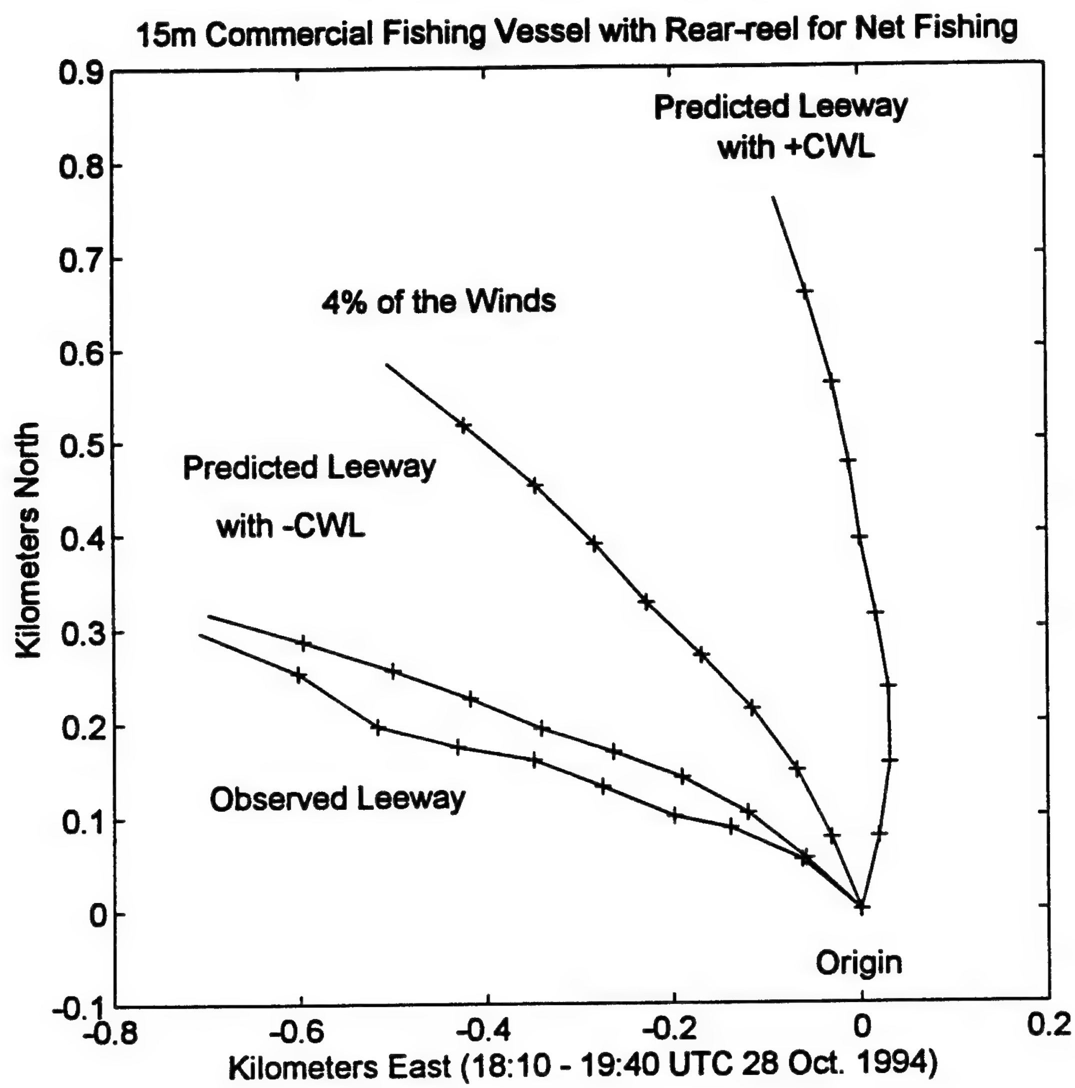


Figure 5-2. The Progressive Vector Diagram of: 4.0% of the Wind, Predicted and Observed Leeway of a 15 m Commercial Fishing Vessel with Rear-reel for Net Fishing, for the period 18:10 - 19:40 UTC 28 Oct. 1994.

5.4 CALCULATION OF THE UNCERTAINTY OF THE PREDICTED LEEWAY VECTOR

The predicted leeway vector sum, that used negative values for the **CWL**, was close to the observed leeway vector sum, Figure 5-2. However, was the end point of the observed leeway within the 95% prediction limits of the predicted leeway?

The linear regression and the 95% prediction limits of the downwind and absolute values of the crosswind component of leeway for the fishing vessel on the wind speed adjusted to 10 meters height are presented in Figures 4-23 and 4-27. The 95% prediction limits were used to estimate the uncertainty in the leeway displacement vectors. The 95% prediction limits are based upon a standard normal distribution of the predicted values about the mean regression. The 95% prediction limits for a normal distribution corresponds to 1.645 times the standard deviation from the mean.

The procedure for implementation of the 95% prediction limits, using second order polynomials, is described in section 3.3.3.2. Second order polynomials (Eq. 3-10, Table 4-17) were then used to calculate the specific 95% limits for the crosswind and downwind components of leeway. The values at both the minimum and maximum 95% prediction limits (for both cross and downwind components) were calculated for each wind speed during the example period. Using the four combinations of the 95% prediction limits from the two components, limits for each leeway prediction were made. The four combinations were: the upper crosswind limit with the upper downwind limit, the upper crosswind limit with the lower downwind limit, the lower crosswind limit with upper downwind limit, and the lower crosswind limit with the lower downwind limit.

In Figure 5-3, the progressive displacements for the four prediction limits about the mean of the positive leeway displacement are presented. A circle that nearly passes through the four end points and centered on the end point of the mean, has a radius of 0.5 kilometers. Figure 5-1 is redrawn as Figure 5-4, except that the two predicted mean leeway progressive displacement vectors are also plotted. At the end point of each predicted mean leeway vector is its uncertainty circle, which is 0.5 kilometers for this example. The observed leeway for a 15 meter commercial fishing vessel was within the 95% prediction limits of predicted leeway.

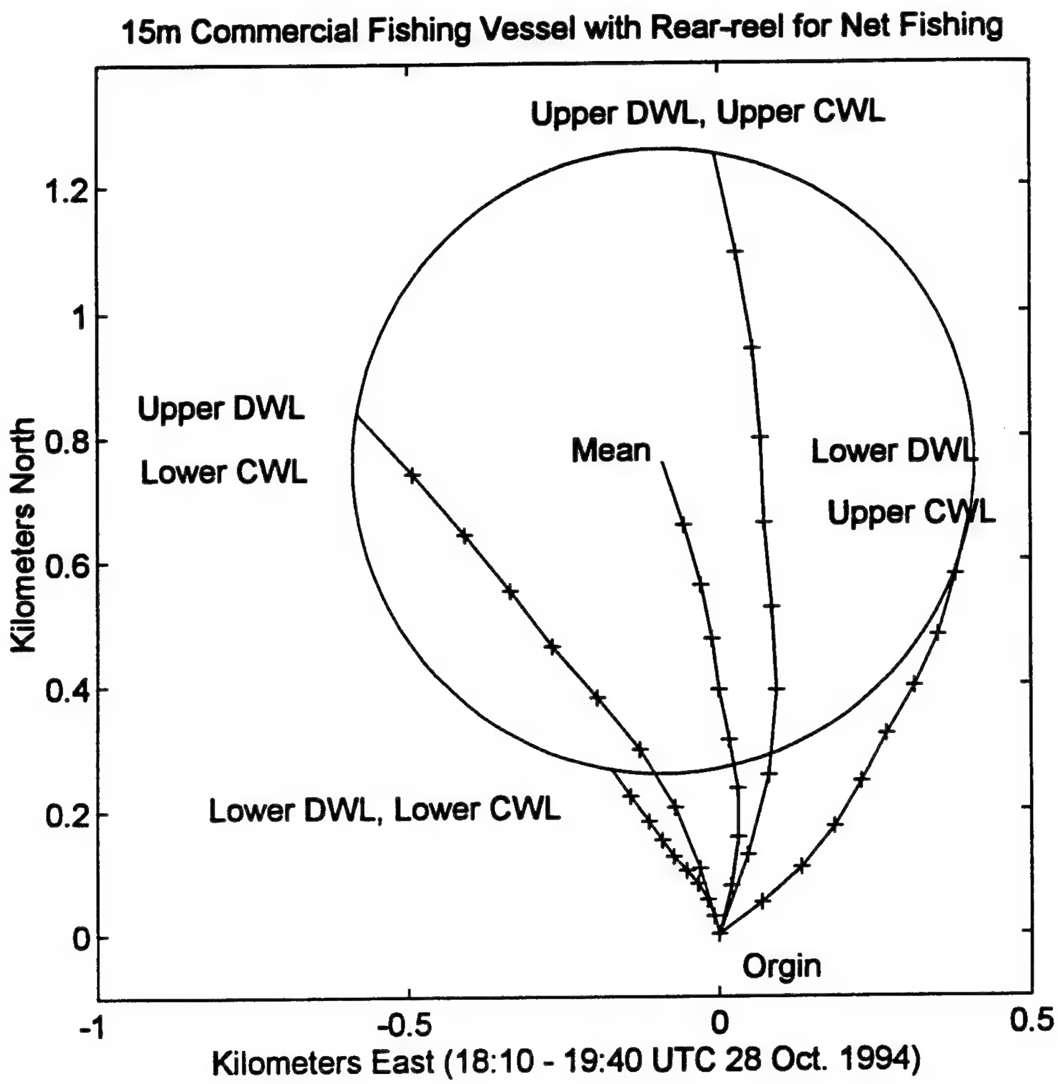


Figure 5-3. The Progressive Vector Diagram of: Mean and the four prediction limits of the Predicted Positive Leeway of a 15 m Commercial Fishing Vessel with Rear-reel for Net Fishing, for the period 18:10 - 19:40 UTC 28 Oct. 1994.

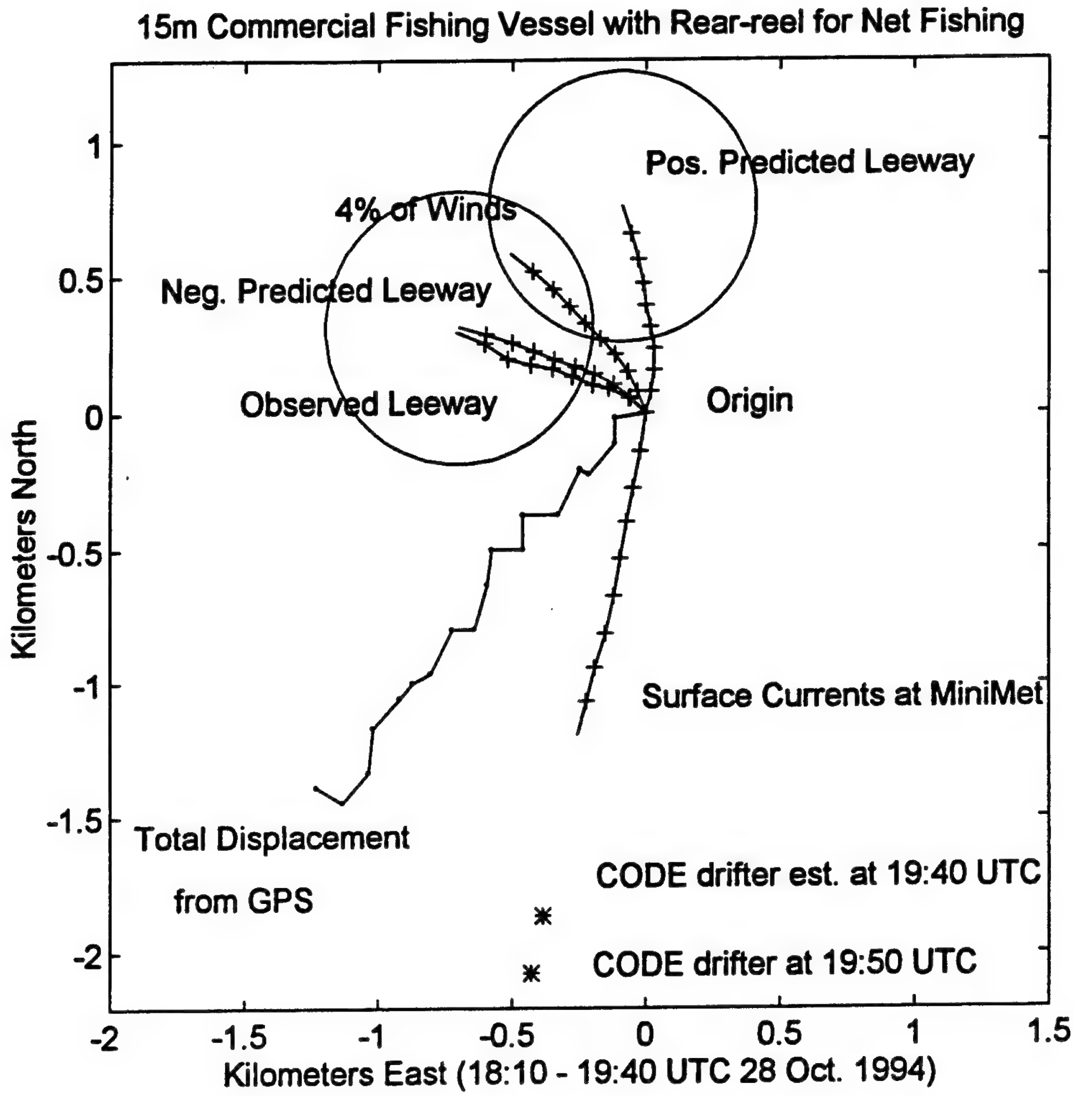


Figure 5-4. The Progressive Vector Diagram of: 4.0% of the Wind, Surface Currents at the MiniMet® buoy, Drift of a CODE drifter, Leeway and Total Displacement of a 15 m Commercial Fishing Vessel with Rear-reel for Net Fishing, for the period 18:10 - 19:40 UTC 28 Oct. 1994. The Mean Predicted leeway and the circles of uncertainty about the end points of the predicted mean leeway displacement vectors are plotted.

5.5 SUMMARY OF THE APPLICATION OF THE UNCERTAINTY TO THE PREDICTION OF LEEWAY

The uncertainty circle represents the approximately 95% prediction contour of the probability distribution for each of the two possible predictions or outcomes. The uncertainty error contains approximately 95% of the area under the probability distribution, assuming a standard normal probability distribution for the predictions. However, since there are two possible outcomes each with approximately 50% chance of occurring, each uncertainty contour contains approximately 47.5% of total distribution. The total distribution is the sum of two distributions. The total probability distribution for this case had two major hills centered on the two predicted endpoints and a small hump where the 95% prediction contours intersect.

The size and shape of the final probability distribution of the predicted leeway uncertainty will be dependent upon several factors: (1) The ratio of the crosswind component to the downwind component of leeway determines the spread of the two outcomes away from the downwind direction. Higher crosswind component of leeway lead to greater separation between the two possible outcomes, separating the final distribution into two hills. For targets with low or no crosswind component of leeway, the final distribution would be hill nearly centered downwind direction. (2) The ratio of the 95% prediction limits of the two leeway components at the wind speed determines whether the uncertainty contour is circular or elliptical. If there was large uncertainty in the crosswind component compared to the uncertainty in the downwind component, the probability distribution would be an ellipse with long axis oriented in the crosswind direction. (3) At wind speeds higher than observed during this study, different leeway behavior is possible, which should not be modeled by simple extrapolation of the equations presented in this report. (4) Local spatial variation in the wind and surface current fields may affect the two predicted leeway trajectories unequally, resulting in further divergence and modification of the predicted distribution.

The relationships between the leeway covariance, surface current covariance, wind covariance and the final distribution of the SAR target will be the subject of the forthcoming research project: Leeway Covariance.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 IMPLICATIONS FOR SEARCH PLANNING

This study was conducted on the high and low drift versions of a Cuban Refugee Raft and a medium displacement fishing vessel. A technique for incorporating the uncertainty of the measured observations of leeway from these experiments into the uncertainty of the prediction of the leeway component of the survivor craft was introduced.

The leeway information presently available in CASP and the National SAR Manual is based on the first seven references in Table 1-1. Presently there is not a class for refugee rafts in CASP or the National SAR manual. The author recommends adding a new class of craft to CASP and the National SAR manual: Refugee Rafts with and without sails.

The leeway rates for the class Medium Displacement sailboats, fishing vessels, such as trawlers, trollers, tuna boats, etc., are found in Chapline, 1960, a study off Hawaii. The leeway rate for Medium displacement vessels in the National SAR manual is 4% of wind speed. This work confirmed this estimate of the leeway rate using an example of a medium displacement vessel.

The technique presented in this report for incorporating the uncertainty of the measured observations of leeway into the uncertainty of the prediction of the leeway component of a survivor craft should be incorporated into future version of CASP. This report presented an example of the use of mean and 95% prediction limits for the prediction of the search area. The upcoming ISARC project, Leeway Covariance, will fully investigate the determination and implementation of leeway covariance for use in CASP.

6.2 RECOMMENDATIONS

A simple model that provides the maximum and minimum leeway speed is recommended for implementation during manual search planning for the Cuban Refugee Raft, for winds less than 10m/s (20 knots). The Cuban Refugee Raft was considered to be a single class with high and low leeway versions. In Figure 6-1, the leeway speed for both the versions of the Cuban Refugee Raft is presented. The dash lines are the linear regressions. The solid lines are minimum and maximum

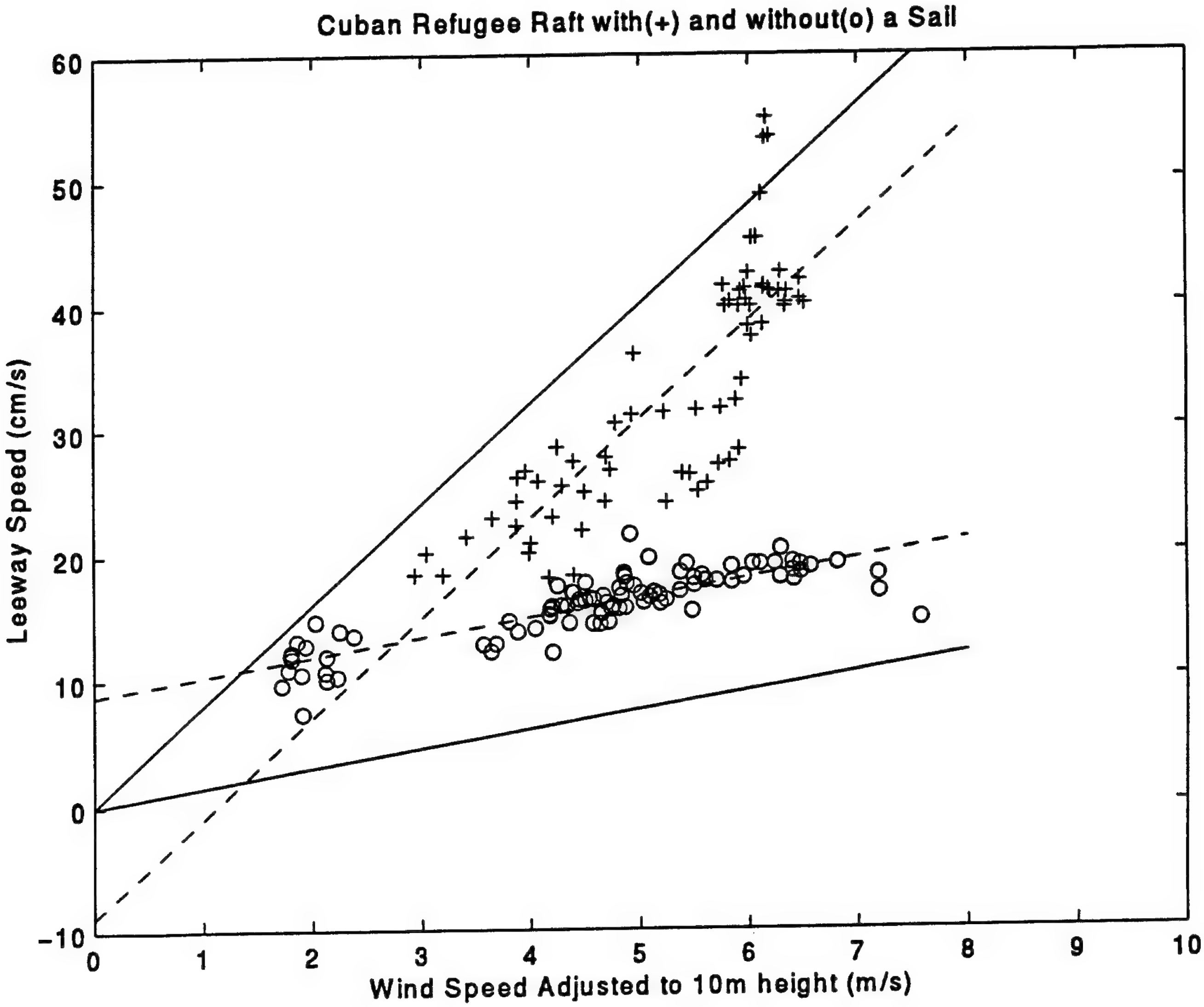


Figure 6-1. The Maximum and Minimum estimations (Solid lines) of Leeway Speed versus Wind Speed at 10m, for the Cuban Refugee Raft. Linear Regressions (Dashed lines) of Cuban Refugee Raft high and low leeway versions: with a Sail (+) and without a Sail (o).

leeway based upon retaining the slope from the regression lines, but passing the lines through the origin, thus providing an upper and lower estimates of the leeway drift of Cuban Refugee rafts. The constrained leeway equation was used for the 15 meter commercial fishing vessel set up for net fishing. Table 6-1 summarizes manual leeway equations for Cuban Refugee Rafts and a 15 meter commercial fishing vessel set up for net fishing. The Cuban Refugee Rafts exhibited a large variation in leeway angles, therefore, the two large ranges of angles are presented for each version. Cuban Refugee Rafts w/o Sail can be expected to drift within 30° of the

downwind direction, while Cuban Refugee Rafts w/Sail can sail off the downwind direction by as much as 45°. The fishing vessel leeway angle was either left or right of the downwind direction by 30° $\pm 15°$.

Table 6-1
Summary of Manual Leeway Equations

(**L** = Leeway speed (cm/s))
(W_{10m} = 10m Wind Speed (m/s))

CLASS	CRAFT	EQUATION	Leeway Angle	W_{10m} (m/s)
Refugee Rafts	w/o sails	$L = 1.5\% \, W_{10m}$	$0° \pm 30°$	2 - 7
	with sails	$L = 8.0\% \, W_{10m}$	$0° \pm 45°$	2 - 7
Medium Displacement fishing vessels	15m Rear-reel Net fishing	$L = 4.0\% \, W_{10m}$	$+30° \pm 15°$ and $-30° \pm 15°$	1 - 9

The statistical models of the leeway components and their prediction limits are recommended for implementation in numerical search planning models. Both plus and minus crosswind equations should be investigated and vector added to the downwind equation. The distribution of the predicted leeway vector can be estimated by applying the technique introduced in Chapter 5.

The linear regression models are recommended when the 10 meter wind speed is less than 10m/s (20 knots). Mean, upper and lower 95% prediction limits equations for Cuban Refugee raft leeway components on the 10 meter wind speed are presented in Table 6-2.

Table 6-2
Summary of Cuban Refugee Raft Leeway Equations

(**DWL** = Downwind Component of Leeway (cm/s))
(**CWL** = Crosswind Component of Leeway (cm/s))
(W_{10m} = 10m Wind Speed (m/s))
(c_1, c_2, and c_3 are coefficients from Eq. 3-10)

Cuban Refugee Rafts without Sails

Mean **DWL** = 1.56% W_{10m} + 8.3 cm/s
Mean **+CWL** = 0.078% W_{10m} + 2.7 cm/s
Mean **-CWL** = -0.078% W_{10m} - 2.7 cm/s

Dependent Variable	Upper Limits			Lower Limits		
	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3
DWL	0.0078	1.4909	11.5154	-0.0078	1.6328	-5.0751
+CWL	0.0077	0.0078	5.8939	-0.0077	0.1484	-0.4897
-CWL	0.0077	-0.1484	0.4897	-0.0077	-0.0078	-5.8939

Cuban Refugee Rafts with Sails

Mean **DWL** = 6.43% W_{10m} - 3.47 cm/s
Mean **+CWL** = 5.19% W_{10m} - 16.2 cm/s
Mean **-CWL** = -5.19% W_{10m} + 16.2 cm/s

Dependent Variable	Upper Limits			Lower Limits		
	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3
DWL	0.0496	5.910	5.2184	-0.0496	6.9572	-12.149
+CWL	0.0889	4.2480	-0.6341	-0.0889	6.1255	-31.770
-CWL	0.0889	-6.1255	31.770	-0.0889	-4.2480	0.6341

For the 15m commercial fishing vessel set up with a rear-reel for net fishing, the linear regression models of the downwind and crosswind components of leeway on wind speed are recommended for use in numerical models. Mean, and upper and lower 95% prediction limits equations for 15m commercial fishing vessel leeway components on the 10 meter wind speed are presented in Table 6-3.

Table 6-3

Summary of
15m Commercial Fishing Vessel with Rear-reel for Net Fishing - Leeway Equations

(**DWL** = Downwind Component of Leeway (cm/s))
(**CWL** = Crosswind Component of Leeway (cm/s))
($\mathbf{W_{10m}}$ = 10m Wind Speed (m/s))
(c_1, c_2, and c_3 are coefficients from Eq. 3-10)

15m Commercial Fishing Vessel with Rear-reel for Net Fishing						
Mean **DWL** = 3.72% $\mathbf{W_{10m}}$ - 0.87 cm/s Mean **+CWL** = 1.41% $\mathbf{W_{10m}}$ + 2.00 cm/s Mean **-CWL** = -1.41% $\mathbf{W_{10m}}$ - 2.00 cm/s						
	Upper Limits			Lower Limits		
Dependent Variable	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3	$c_1 (W_{10m})^2$	$c_2 (W_{10m})$	c_3
DWL	0.0070	5.8787	3.6507	-0.0070	3.3737	-7.6245
+CWL	0.0070	1.3380	8.7976	-0.0070	1.4721	-4.8039
-CWL	0.0070	-1.4721	4.8039	-0.0070	-1.3380	-8.7976

6.3 FUTURE WORK

The direct method of determining leeway can be applied without modification to medium and large sized SAR targets. Medium targets that should be studied include open dories, including the double ended Caribbean dory, the 'yola', and vee- and flat- bottom outboard motor boats. Medium targets will need to be tended using larger sized vessels, which can also be used as leeway targets. Larger SAR targets that should be studied include commercial fishing vessels -- stern trawlers, shrimpers, long-liners, and sport fishing boats. The direct method of determining leeway can also be applied to sailboats, though they present greater logistical problems during the deployment and recovery portion of the leeway study. Sailboat leeway targets should include deep draft mono-hull ocean sailboat -- upright with and without a mast, and capsized; capsized catamarans and trimarians.

Smaller leeway targets such as Person-In-the-Water (PIWs), PIWs in survivor suits, sea kayaks, and sail board will require the modification of the direct method. The towed Interocean S4® EMCM will have to be replaced by a suitable small current meter onboard the leeway target that does not measurable effect the leeway behavior of the target.

The implication of using the 95% prediction limits in numerical models of search should be further investigated under the ISARC Project, Leeway Covariance. It should also be determined whether the 95% prediction limits can be determined directly or indirectly through estimations from past leeway studies.

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APPENDIX A

LEEWAY DATA

This appendix lists the 10 minute averaged data from the three leeway craft.

Column 1) The date of the 10 minute sample.

Column 2) The UTC time of the center of the 10 minute average in hours.

Column 3) The Crosswind component of leeway in cm/s.

Column 4) The Downwind component of leeway in cm/s.

Column 5) The Wind Speed adjusted to 10 meter height in m/s.

Column 6) The Downwind Direction of the Wind in north coordinates (degrees).

Column 7) The East component of leeway in cm/s.

Column 8) The North component of leeway in cm/s.

Column 9) The leeway speed in cm/s.

Refugee Raft without Sail

DAY 1994	UTC Hour	Crosswind	Downwind	Windsp10	WindDirT	Lee East	Lee North	LeeSpeed
27-Oct-94	18.42	-3.32	14.27	7.57	183.69	2.39	-14.45	14.65
27-Oct-94	18.58	-3.22	16.51	7.19	183.63	2.17	-16.68	16.82
27-Oct-94	18.75	-3.23	17.92	7.18	183.63	2.09	-18.09	18.21
27-Oct-94	18.92	-5.79	18.23	6.81	186.33	3.75	-18.76	19.13
27-Oct-94	19.08	-4.26	18.34	6.56	185.35	2.53	-18.66	18.83
27-Oct-94	19.25	-3.94	17.36	6.41	188.09	1.46	-17.74	17.80
27-Oct-94	19.42	-5.59	19.49	6.29	186.22	3.45	-19.99	20.28
27-Oct-94	19.58	-1.98	17.90	5.95	179.70	2.07	-17.89	18.01
27-Oct-94	19.75	-3.13	15.02	5.48	175.03	4.42	-14.69	15.34
27-Oct-94	19.92	-2.19	16.09	5.24	173.15	4.10	-15.72	16.24
27-Oct-94	20.08	-5.49	14.64	4.87	174.88	6.78	-14.09	15.64
27-Oct-94	20.25	-4.90	15.75	5.09	178.55	5.29	-15.62	16.49
27-Oct-94	20.42	-5.73	15.62	5.18	182.24	5.11	-15.84	16.64
27-Oct-94	20.58	-7.50	15.11	5.13	191.46	4.35	-16.30	16.87
27-Oct-94	20.75	-6.91	15.28	5.01	191.42	3.75	-16.35	16.77
28-Oct-94	15.25	0.64	7.25	1.91	11.19	2.04	6.99	7.28
28-Oct-94	15.42	-0.83	9.97	2.13	0.05	-0.82	9.97	10.00
28-Oct-94	15.58	-3.50	9.61	2.23	19.80	-0.04	10.23	10.23
28-Oct-94	15.75	-2.99	10.03	1.90	18.46	0.35	10.46	10.47
28-Oct-94	15.92	-3.56	10.02	2.12	10.57	-1.66	10.50	10.63
28-Oct-94	16.08	-2.27	11.80	1.80	3.33	-1.58	11.91	12.01
28-Oct-94	16.25	-5.07	9.57	1.78	18.98	-1.68	10.70	10.83
28-Oct-94	16.42	-1.70	12.11	1.81	359.53	-1.79	12.09	12.23
28-Oct-94	16.58	-3.00	11.50	2.13	3.19	-2.36	11.65	11.88
28-Oct-94	16.75	-2.34	11.50	1.81	357.97	-2.74	11.41	11.74
28-Oct-94	16.92	-3.50	8.91	1.72	350.76	-4.89	8.23	9.57
28-Oct-94	17.08	-4.01	13.34	2.25	356.20	-4.88	13.04	13.93
28-Oct-94	17.25	-3.47	12.30	1.94	350.93	-5.37	11.60	12.78
28-Oct-94	17.42	-2.82	14.40	2.03	355.41	-3.97	14.12	14.67
28-Oct-94	17.58	-0.72	13.08	1.86	342.50	-4.62	12.26	13.10
28-Oct-94	17.75	-3.26	13.14	2.38	350.26	-5.43	12.40	13.54
1-Nov-94	15.42	-4.95	15.29	5.03	86.63	14.97	5.84	16.07
1-Nov-94	15.58	-2.87	15.31	4.81	83.32	14.87	4.63	15.58
1-Nov-94	15.75	-2.55	15.32	4.74	82.89	14.89	4.43	15.53
1-Nov-94	15.92	-1.65	14.42	4.72	84.72	14.20	2.97	14.51
1-Nov-94	16.08	-2.89	14.11	4.57	87.30	13.96	3.55	14.40
1-Nov-94	16.25	-2.53	11.84	4.20	89.77	11.83	2.58	12.11
1-Nov-94	16.42	-2.97	14.33	3.80	93.08	14.47	2.19	14.63
1-Nov-94	16.58	-3.52	11.71	3.64	98.28	12.09	1.79	12.23
1-Nov-94	16.75	-4.65	12.99	3.88	104.17	13.74	1.33	13.80
1-Nov-94	16.92	-5.49	14.82	4.34	107.10	15.78	0.89	15.81
1-Nov-94	17.08	-4.73	15.31	4.70	105.34	16.01	0.51	16.02
1-Nov-94	17.25	-3.28	15.46	4.76	98.01	15.76	1.09	15.80
1-Nov-94	17.42	-2.71	14.11	4.64	87.37	13.97	3.35	14.37
1-Nov-94	17.58	-1.63	16.32	4.54	78.35	15.65	4.90	16.40
1-Nov-94	18.42	1.23	12.80	3.68	64.47	12.08	4.40	12.86
1-Nov-94	18.58	-1.11	12.75	3.57	61.30	10.66	7.10	12.80
1-Nov-94	18.75	-1.30	13.99	4.04	66.24	12.28	6.83	14.05
1-Nov-94	18.92	-3.73	16.77	4.81	73.09	14.96	8.45	17.18
1-Nov-94	19.08	-4.45	18.60	5.43	77.30	17.17	8.43	19.13

Refugee Raft without Sail

DAY 1994	UTC Hour	Crosswind	Downwind	Windsp10	WindDirT	Lee East	Lee North	LeeSpeed
1-Nov-94	19.25	-3.60	17.79	5.57	78.12	16.67	7.19	18.15
1-Nov-94	19.42	-4.34	16.37	5.37	77.22	15.01	7.85	16.94
1-Nov-94	19.58	-4.89	19.00	5.08	76.31	17.30	9.25	19.62
1-Nov-94	19.75	-3.77	21.17	4.91	76.98	19.78	8.45	21.50
1-Nov-94	19.92	-5.00	17.69	4.85	78.72	16.37	8.37	18.38
1-Nov-94	20.08	-5.72	17.17	4.86	80.30	15.96	8.53	18.09
1-Nov-94	20.25	-3.84	17.16	4.88	80.72	16.32	6.56	17.59
2-Nov-94	14.42	-4.88	14.39	4.65	184.94	3.62	-14.75	15.19
2-Nov-94	14.58	-4.73	17.01	4,50	186.30	2.83	-17.43	17.66
2-Nov-94	14.75	-4.95	15.53	4.44	186.65	3.12	-16.00	16.30
2-Nov-94	14.92	-3.54	15.62	4.43	185.92	1.91	-15.90	16.01
2-Nov-94	15.08	-4.21	16.34	4.39	184.32	2.97	-16.61	16.88
2-Nov-94	15.25	-2.81	15.58	4.28	181.93	2.29	-15.67	15.83
2-Nov-94	15.42	-1.86	14.92	4.18	178.59	2.22	-14.87	15.03
2-Nov-94	15.58	-1.94	15.44	4.18	174.34	3.45	-15.17	15.56
2-Nov-94	15.75	-1.42	14.40	4.36	169.79	3.95	-13.92	14.47
2-Nov-94	15.92	-1.40	15.22	4.64	166.18	5.00	-14.44	15.28
2-Nov-94	16.08	-1.12	17.33	4.95	164.31	5.76	-16.38	17.37
2-Nov-94	16.25	-1.19	15.92	5.19	164.34	5.45	-15.01	15.96
2-Nov-94	16.42	-1.64	18.36	5.37	165.34	6.24	-17.35	18.44
2-Nov-94	16.58	-2.54	17.21	5.50	166.31	6.54	-16.12	17.40
2-Nov-94	16.75	-1.73	17.67	5.60	166.55	5.79	-16.78	17.75
2-Nov-94	16.92	-2.23	17.58	5.70	166.14	6.37	-16.53	17.72
2-Nov-94	17.08	-0.94	18.85	5.84	165.32	5.69	-17.99	18.87
2-Nov-94	17.25	-0.59	19.06	6.03	164.36	5.71	-18.19	19.07
2-Nov-94	17.42	-1.16	19.03	6.24	163.59	6.49	-17.93	19.07
2-Nov-94	17.58	-0.83	19.19	6.40	163.31	6.30	-18.15	19.21
2-Nov-94	17.75	-1.74	18.33	6.47	163.66	6.82	-17.10	18.41
2-Nov-94	17.92	-1.24	18.98	6.47	164.43	6.29	-17.95	19.02
2-Nov-94	18.08	-2.65	18.34	6.40	165.31	7.22	-17.07	18.53
2-Nov-94	18.25	-1.75	17.91	6.28	166.08	6.01	-16.97	18.00
2-Nov-94	18.42	-2.27	18.93	6.10	166.96	6.49	-17.93	19.07
2-Nov-94	18.58	-2.49	17.43	5.84	168.30	5.97	-16.57	17.61
2-Nov-94	18.75	-2.87	17.72	5.49	170.32	5.81	-16.98	17.95
2-Nov-94	18.92	-2.69	16.57	5.13	172.16	4.93	-16.05	16.79
2-Nov-94	19.08	-2.75	16.37	4.83	172.32	4.91	-15.85	16.60
2-Nov-94	19.25	-2.79	16.36	4.66	169.63	5.69	-15.59	16.59
2-Nov-94	19.42	-2.15	16.18	4.58	165.77	6.06	-15.16	16.32
2-Nov-94	19.58	-1.06	16.17	4.50	163.31	5.66	-15.19	16.21
2-Nov-94	19.75	-1.54	16.83	4.38	164.04	6.11	-15.75	16.90
2-Nov-94	19.92	-3.85	16.99	4.25	166.54	7.70	-15.62	17.42
2-Nov-94	20.08	-3.43	14.73	4.17	168.31	6.34	-13.73	15.12
2-Nov-94	20.25	-3.30	15.40	4.20	167.36	6.59	-14.31	15.75

Refugee Raft with Sail

DAY 1994	UTC Hour	Crosswind	Downwind	Windsp10	WindDirTo	Lee East	Lee North	Lee Speed
28-Oct-94	18.75	3.87	17.94	2.94	322.74	-7.78	16.62	18.35
28-Oct-94	18.92	5.55	19.28	3.04	315.75	-9.48	17.68	20.06
28-Oct-94	19.08	5.92	17.36	3.20	311.32	-9.13	15.91	18.34
28-Oct-94	19.25	5.86	20.57	3.41	310.94	-11.70	17.90	21.39
28-Oct-94	19.42	7.51	21.58	3.65	312.91	-10.69	20.19	22.85
28-Oct-94	19.58	5.44	25.46	3.88	315.30	-14.04	21.93	26.04
28-Oct-94	19.75	-0.25	25.74	4.07	316.86	-17.78	18.61	25.74
28-Oct-94	19.92	0.55	28.43	4.24	317.50	-18.81	21.33	28.44
31-Oct-94	15.08	13.89	33.17	4.95	20.30	24.53	26.29	35.96
31-Oct-94	15.25	11.87	27.98	4.78	22.66	21.74	21.25	30.40
31-Oct-94	15.42	11.66	25.07	4.69	24.49	21.00	17.98	27.64
31-Oct-94	15.58	12.20	23.67	4.73	25.31	21.15	16.18	26.63
31-Oct-94	15.75	6.24	30.41	4.93	24.80	18.42	24.99	31.04
31-Oct-94	15.92	6.52	30.55	5.22	23.08	17.97	25.55	31.24
31-Oct-94	16.08	7.62	30.48	5.52	20.33	17.74	25.94	31.42
31-Oct-94	16.25	8.43	30.41	5.75	16.83	16.88	26.67	31.56
31-Oct-94	16.42	8.43	31.05	5.89	13.72	15.55	28.17	32.17
31-Oct-94	16.58	8.16	32.82	5.94	12.31	14.97	30.33	33.82
31-Oct-94	16.75	0.62	28.21	5.91	13.51	7.19	27.28	28.21
31-Oct-94	16.92	-6.25	26.54	5.83	16.56	1.58	27.22	27.27
31-Oct-94	17.08	-3.64	26.77	5.72	20.29	5.86	26.37	27.01
31-Oct-94	17.25	-3.16	25.32	5.62	23.56	7.22	24.47	25.52
31-Oct-94	17.42	-2.58	24.74	5.53	25.98	8.52	23.37	24.88
31-Oct-94	17.58	-1.06	26.22	5.46	27.31	11.09	23.79	26.25
31-Oct-94	17.75	-3.60	26.07	5.39	27.40	8.80	24.80	26.32
31-Oct-94	17.92	-6.75	23.05	5.24	26.60	4.28	23.63	24.01
31-Oct-94	18.92	5.66	25.96	3.96	8.42	9.40	24.85	26.57
31-Oct-94	19.08	5.58	24.75	4.29	5.33	7.85	24.12	25.37
31-Oct-94	19.25	2.55	21.73	4.47	2.92	3.65	21.57	21.88
31-Oct-94	19.42	2.49	24.74	4.49	0.70	2.79	24.71	24.87
31-Oct-94	19.58	4.79	26.89	4.39	358.32	4.00	27.02	27.31
31-Oct-94	19.75	4.61	22.44	4.20	355.79	2.95	22.72	22.91
31-Oct-94	19.92	6.03	19.93	4.00	354.66	4.15	20.41	20.82
31-Oct-94	20.08	5.26	21.59	3.87	357.28	4.23	21.82	22.23
31-Oct-94	20.25	1.89	24.08	3.87	5.21	4.07	23.81	24.16
31-Oct-94	20.42	0.73	20.05	3.99	16.72	6.47	18.99	20.06
31-Oct-94	20.58	-3.60	17.73	4.17	30.23	5.82	17.13	18.09
31-Oct-94	20.75	-5.47	17.42	4.39	45.21	8.51	16.15	18.25
31-Oct-94	20.92	-5.74	23.41	4.68	58.11	16.85	17.24	24.10
3-Nov-94	16.25	-34.37	40.95	6.19	228.73	-8.11	-52.84	53.46
3-Nov-94	16.42	-37.65	39.97	6.16	230.15	-6.56	-54.52	54.91
3-Nov-94	16.58	-36.62	38.70	6.15	231.31	-7.31	-52.77	53.28
3-Nov-94	16.75	-25.00	41.97	6.12	231.30	-17.12	-45.75	48.85
3-Nov-94	16.92	-22.30	39.49	6.07	230.66	-16.40	-42.28	45.35
3-Nov-94	17.08	-16.62	42.16	6.03	230.31	-21.83	-39.72	45.32
3-Nov-94	17.25	-16.95	38.98	6.00	230.94	-19.58	-37.73	42.51
3-Nov-94	17.42	-19.09	36.60	5.96	232.15	-17.19	-37.53	41.28
3-Nov-94	17.58	-15.18	36.85	5.91	233.30	-20.47	-34.19	39.85
3-Nov-94	17.75	-16.80	36.54	5.83	233.86	-19.59	-35.12	40.22
3-Nov-94	17.92	-20.96	35.84	5.77	233.81	-16.54	-38.08	41.52

Refugee Raft with Sail

DAY 1994	UTC Hour	Crosswind	Downwind	Windsp10	WindDirTo	Lee East	Lee North	Lee Speed
3-Nov-94	18.08	-19.23	34.89	5.79	233.31	-16.49	-36.27	39.84
3-Nov-94	18.25	-17.89	36.92	5.93	232.61	-18.47	-36.63	41.02
3-Nov-94	18.42	-15.00	38.47	6.14	232.14	-21.17	-35.45	41.29
3-Nov-94	18.58	-19.39	34.77	6.34	232.31	-15.66	-36.60	39.81
3-Nov-94	18.75	-15.14	39.18	6.47	233.31	-22.37	-35.55	42.00
3-Nov-94	18.92	-15.00	37.17	6.52	234.79	-21.72	-33.69	40.08
3-Nov-94	19.08	-16.33	36.95	6.47	236.30	-21.69	-34.09	40.40
3-Nov-94	19.25	-12.17	38.28	6.34	237.54	-25.77	-30.81	40.16
3-Nov-94	19.42	-12.44	39.08	6.20	238.76	-26.96	-30.91	41.02
3-Nov-94	19.58	-14.30	35.58	6.13	240.30	-23.82	-30.05	38.35
3-Nov-94	19.75	-13.64	38.87	6.19	242.21	-28.03	-30.19	41.19
3-Nov-94	19.92	-15.37	39.73	6.29	243.55	-28.72	-31.45	42.60
3-Nov-94	20.08	-17.07	37.31	6.35	243.32	-25.67	-32.01	41.03
3-Nov-94	20.25	-17.49	37.08	6.28	241.01	-23.96	-33.27	41.00
3-Nov-94	20.42	-18.80	37.02	6.14	238.22	-21.57	-35.48	41.52
3-Nov-94	20.58	-14.46	37.14	6.02	237.30	-23.44	-32.22	39.85
3-Nov-94	20.75	-11.81	38.58	5.98	239.94	-27.48	-29.55	40.35
3-Nov-94	20.92	-16.89	34.29	6.00	243.98	-23.41	-30.22	38.22
3-Nov-94	21.08	-14.59	34.43	6.03	246.31	-25.66	-27.19	37.39

15m Fishing Vessel

Day 1994	UTC hour	Crosswind	Downwind	Windsp10m	WindDirT	Lee East	Lee North	LeeSpeed
25-Oct-94	14.93	9.83	19.06	4.72	165.95	-4.91	-20.87	21.44
25-Oct-94	15.10	14.99	21.72	5.53	166.30	-9.42	-24.65	26.39
25-Oct-94	15.27	13.19	18.35	5.93	170.47	-9.97	-20.28	22.60
25-Oct-94	15.43	20.09	17.37	6.01	176.35	-18.94	-18.61	26.55
25-Oct-94	15.60	11.78	21.95	5.93	181.29	-12.27	-21.68	24.91
25-Oct-94	15.77	12.51	22.29	5.84	183.07	-13.68	-21.59	25.56
25-Oct-94	15.93	18.82	19.60	5.77	182.75	-19.74	-18.68	27.17
25-Oct-94	16.10	13.45	25.03	5.72	182.31	-14.45	-24.46	28.41
25-Oct-94	16.27	9.81	25.01	5.69	183.33	-11.24	-24.40	26.87
25-Oct-94	16.43	13.84	23.98	5.68	185.34	-16.01	-22.58	27.68
25-Oct-94	16.60	12.98	23.61	5.71	187.30	-15.87	-21.77	26.94
26-Oct-94	14.75	-5.07	2.45	1.41	43.00	-2.04	5.25	5.63
26-Oct-94	14.92	-5.62	5.42	1.41	28.00	-2.42	7.43	7.81
26-Oct-94	15.08	-2.58	5.91	1.44	26.00	0.27	6.44	6.45
26-Oct-94	15.25	-1.21	8.46	1.58	24.00	2.34	8.22	8.54
26-Oct-94	15.42	-1.06	6.92	1.65	4.00	-0.57	6.98	7.00
26-Oct-94	15.58	-4.16	7.62	2.05	355.00	-4.81	7.23	8.68
26-Oct-94	15.75	-0.54	8.34	1.95	348.00	-2.27	8.04	8.35
26-Oct-94	15.92	-3.02	8.18	2.46	339.00	-5.75	6.55	8.72
26-Oct-94	16.08	-4.90	10.51	2.66	348.00	-6.98	9.26	11.60
26-Oct-94	16.25	-4.33	12.12	2.76	342.00	-7.86	10.19	12.87
26-Oct-94	16.42	-4.12	11.34	2.56	335.00	-8.53	8.53	12.06
26-Oct-94	16.58	-4.98	12.50	2.56	329.00	-10.70	8.15	13.45
26-Oct-94	16.75	-3.34	12.43	2.66	326.00	-9.72	8.43	12.87
26-Oct-94	16.92	0.92	12.17	3.07	316.00	-7.79	9.39	12.21
26-Oct-94	17.08	2.82	12.06	2.87	311.00	-7.25	10.04	12.38
26-Oct-94	16.42	-7.11	17.21	4.40	173.68	8.96	-16.32	18.62
27-Oct-94	16.58	-6.65	20.43	4.54	169.16	10.37	-18.81	21.48
27-Oct-94	16.75	-7.82	20.22	5.61	166.56	12.30	-17.85	21.68
27-Oct-94	16.92	-17.72	28.53	8.78	165.78	24.19	-23.30	33.58
27-Oct-94	17.08	-15.98	31.47	7.97	170.43	20.99	-28.38	35.30
27-Oct-94	17.25	-18.93	25.47	8.10	176.93	20.26	-24.42	31.74
27-Oct-94	18.25	-11.48	22.69	7.59	182.86	10.33	-23.23	25.43
27-Oct-94	18.42	-9.96	23.33	7.59	180.99	9.55	-23.50	25.37
27-Oct-94	18.58	-14.91	21.44	7.58	183.75	13.47	-22.37	26.12
27-Oct-94	18.75	-13.04	20.22	7.37	180.93	12.71	-20.43	24.06
27-Oct-94	18.92	-11.67	23.09	7.05	182.71	10.57	-23.62	25.87
27-Oct-94	19.08	-11.55	20.50	6.51	185.34	9.59	-21.49	23.53
27-Oct-94	19.25	-7.79	21.38	6.08	185.21	5.82	-22.00	22.75
27-Oct-94	19.42	-13.40	18.73	5.96	187.90	10.70	-20.39	23.03
27-Oct-94	19.58	-10.49	20.14	5.77	183.26	9.32	-20.71	22.71
27-Oct-94	19.75	-12.89	16.28	5.33	184.91	11.45	-17.32	20.77
27-Oct-94	19.92	-10.84	17.54	5.25	176.74	11.82	-16.89	20.62
27-Oct-94	20.08	-5.74	19.15	4.73	172.12	8.31	-18.18	19.99
27-Oct-94	20.25	-7.33	19.14	4.81	179.25	7.58	-19.04	20.50
28-Oct-94	14.75	4.37	2.81	1.64	50.69	4.95	-1.60	5.20
28-Oct-94	14.92	1.42	-0.77	1.29	26.92	0.91	-1.33	1.61
28-Oct-94	15.08	0.33	0.78	1.70	17.52	0.55	0.65	0.85
28-Oct-94	15.25	3.46	1.28	1.72	3.04	3.52	1.09	3.69
28-Oct-94	15.42	-5.99	4.51	2.15	4.41	-5.62	4.96	7.50

15m Fishing Vessel

Day 1994	UTC hour	Crosswind	Downwind	Windsp10m	WindDirT	Lee East	Lee North	LeeSpeed
28-Oct-94	15.58	-2.98	7.23	2.16	13.31	-1.24	7.72	7.82
28-Oct-94	15.75	0.78	9.01	1.87	8.37	2.09	8.80	9.04
28-Oct-94	15.92	-3.64	5.53	1.89	3.64	-3.28	5.75	6.62
28-Oct-94	16.08	-3.08	7.97	1.91	0.12	-3.06	7.98	8.54
28-Oct-94	16.25	-4.43	6.07	1.61	6.22	-3.75	6.52	7.52
28-Oct-94	16.42	-3.62	7.79	1.95	355.47	-4.23	7.48	8.59
28-Oct-94	16.58	-6.86	5.93	2.27	355.87	-7.27	5.42	9.07
28-Oct-94	16.75	-5.45	4.30	1.98	358.53	-5.56	4.16	6.94
28-Oct-94	16.92	-4.48	5.51	1.84	336.75	-6.29	3.30	7.10
28-Oct-94	17.08	-5.57	8.08	2.22	356.53	-6.05	7.73	9.82
28-Oct-94	17.25	-5.09	8.93	2.15	347.92	-6.85	7.67	10.28
28-Oct-94	17.42	-6.27	8.42	1.96	351.61	-7.43	7.42	10.50
28-Oct-94	17.58	-3.98	11.97	2.50	346.33	-6.70	10.69	12.61
28-Oct-94	18.25	-7.43	11.53	3.37	343.68	-10.37	8.98	13.72
28-Oct-94	18.42	-9.66	10.09	3.29	338.20	-12.72	5.78	13.97
28-Oct-94	18.58	-7.52	6.88	3.33	328.82	-10.00	1.99	10.19
28-Oct-94	18.75	-6.50	12.35	3.27	320.38	-12.88	5.36	13.95
28-Oct-94	18.92	-5.94	11.73	3.39	318.33	-12.23	4.82	13.15
28-Oct-94	19.08	-9.38	10.16	3.46	322.26	-13.63	2.29	13.82
28-Oct-94	19.25	-8.52	12.10	3.69	319.36	-14.35	3.64	14.80
28-Oct-94	19.42	-3.62	16.70	4.23	315.88	-14.22	9.47	17.09
28-Oct-94	19.58	-7.08	17.69	4.45	313.96	-17.65	7.18	19.05
31-Oct-94	14.92	-9.36	12.69	5.27	16.25	-5.43	14.81	15.77
31-Oct-94	15.08	-9.29	12.75	5.15	18.95	-4.65	15.07	15.77
31-Oct-94	15.25	-10.14	11.76	5.01	24.19	-4.43	14.89	15.53
31-Oct-94	15.42	-8.03	12.67	4.77	27.66	-1.23	14.95	15.00
31-Oct-94	15.58	-9.14	8.49	4.63	30.37	-3.59	11.95	12.47
31-Oct-94	15.75	-6.49	11.33	5.09	19.84	-2.26	12.86	13.06
31-Oct-94	15.92	-9.91	13.70	5.69	20.28	-4.55	16.28	16.91
31-Oct-94	16.08	-10.53	13.39	5.59	17.84	-5.93	15.97	17.03
31-Oct-94	16.25	-9.23	14.72	5.69	15.43	-4.98	16.65	17.38
31-Oct-94	16.42	-9.39	13.52	5.88	9.45	-7.04	14.87	16.46
31-Oct-94	16.58	-10.83	14.49	5.98	14.05	-6.99	16.68	18.09
31-Oct-94	16.75	-9.98	12.11	5.35	17.76	-5.81	14.57	15.69
31-Oct-94	16.92	-11.20	13.06	5.45	16.21	-7.11	15.67	17.21
31-Oct-94	17.08	-10.86	10.90	5.36	24.35	-5.40	14.41	15.38
31-Oct-94	17.25	-11.45	12.54	5.46	25.47	-4.95	16.25	16.99
31-Oct-94	18.92	-6.35	18.99	4.74	5.20	-4.61	19.49	20.03
31-Oct-94	19.08	-8.66	17.52	4.53	3.75	-7.50	18.05	19.54
31-Oct-94	19.25	-6.34	16.40	3.93	359.26	-6.56	16.32	17.59
31-Oct-94	19.42	-3.79	14.38	4.28	352.85	-5.55	13.79	14.87
31-Oct-94	19.58	-9.68	17.55	4.73	356.85	-10.62	16.99	20.04
31-Oct-94	19.75	-9.97	14.55	4.21	0.54	-9.83	14.65	17.64
31-Oct-94	19.92	-8.04	12.60	3.79	3.34	-7.29	13.05	14.95
31-Oct-94	20.08	-6.58	13.47	3.97	2.68	-5.94	13.76	14.99
31-Oct-94	20.25	-8.24	13.86	4.55	2.65	-7.59	14.23	16.12
31-Oct-94	20.42	-8.23	13.65	3.93	8.88	-6.03	14.76	15.94
31-Oct-94	20.58	-9.31	12.68	4.02	19.86	-4.45	15.09	15.73
31-Oct-94	20.75	-8.64	11.52	4.51	32.19	-1.18	14.35	14.40
1-Nov-94	15.58	-11.64	17.44	5.15	86.11	16.61	12.80	20.97

15m Fishing Vessel

Day 1994	UTC hour	Crosswind	Downwind	Windsp10m	WindDirT	Lee East	Lee North	LeeSpeed
1-Nov-94	15.75	-9.38	17.86	4.84	82.64	16.51	11.59	20.17
1-Nov-94	15.92	-15.27	17.57	4.68	89.33	17.39	15.47	23.28
1-Nov-94	16.08	-12.64	18.04	4.67	87.94	17.57	13.28	22.03
1-Nov-94	16.25	-12.69	16.06	4.01	89.78	16.01	12.75	20.47
1-Nov-94	16.42	-11.00	14.56	4.07	94.99	15.46	9.70	18.25
1-Nov-94	16.58	-11.54	13.79	3.78	98.10	15.28	9.48	17.98
1-Nov-94	16.75	-10.50	15.65	4.36	101.88	17.48	7.05	18.85
1-Nov-94	16.92	-13.76	13.82	4.39	109.13	17.57	8.46	19.50
1-Nov-94	17.08	-11.05	18.09	4.71	103.08	20.12	6.67	21.20
1-Nov-94	17.25	-8.67	16.38	4.19	93.01	16.82	7.80	18.54
1-Nov-94	17.42	-8.47	16.32	4.05	82.00	14.98	10.66	18.38
1-Nov-94	17.58	-12.61	18.87	4.60	78.36	15.93	16.16	22.69
1-Nov-94	18.42	-5.01	8.41	4.55	66.94	5.77	7.90	9.78
1-Nov-94	18.58	-3.95	14.19	3.83	59.14	10.16	10.67	14.73
1-Nov-94	18.75	-5.10	14.97	4.59	72.03	12.67	9.47	15.82
1-Nov-94	18.92	-8.42	15.51	4.96	75.23	12.85	12.09	17.65
1-Nov-94	19.08	-8.95	17.93	5.74	75.77	15.18	13.09	20.04
1-Nov-94	19.25	-8.28	16.16	5.10	75.94	13.67	11.96	18.16
1-Nov-94	19.42	-9.75	12.89	4.53	73.39	9.57	13.03	16.16
1-Nov-94	19.58	-8.41	15.51	5.03	78.47	13.52	11.34	17.65
1-Nov-94	19.75	-10.22	18.35	5.80	74.06	14.83	14.86	21.00
1-Nov-94	19.92	-8.52	17.76	5.34	76.28	15.23	12.49	19.69
1-Nov-94	20.08	-11.20	15.19	5.22	81.43	13.35	13.34	18.87
2-Nov-94	14.58	-14.92	17.80	5.23	184.74	13.40	-18.97	23.22
2-Nov-94	14.75	-17.62	17.68	5.21	186.66	15.45	-19.60	24.96
2-Nov-94	14.92	-14.84	19.41	5.02	183.84	13.51	-20.36	24.44
2-Nov-94	15.08	-15.13	17.53	5.11	184.89	13.58	-18.75	23.15
2-Nov-94	15.25	-13.39	21.17	4.91	182.08	12.61	-21.64	25.05
2-Nov-94	15.42	-12.34	18.58	4.82	179.35	12.55	-18.44	22.30
2-Nov-94	15.58	-13.31	19.58	4.73	172.07	15.89	-17.56	23.68
2-Nov-94	15.75	-9.32	19.55	4.62	172.09	11.92	-18.09	21.66
2-Nov-94	15.92	-13.60	20.70	5.04	165.90	18.23	-16.77	24.77
2-Nov-94	16.08	-13.55	20.48	5.24	168.75	17.28	-17.45	24.56
2-Nov-94	16.25	-13.02	20.10	5.24	166.97	17.22	-16.65	23.95
2-Nov-94	16.42	-12.51	21.02	5.33	167.04	16.90	-17.68	24.46
2-Nov-94	16.58	-12.84	19.69	5.43	166.18	17.17	-16.05	23.50
2-Nov-94	16.75	-15.66	21.84	5.85	165.35	20.67	-17.17	26.87
2-Nov-94	16.92	-18.00	20.66	5.84	166.33	22.37	-15.82	27.40
2-Nov-94	17.08	-17.48	22.79	5.94	166.39	22.35	-18.03	28.72
2-Nov-94	17.92	-8.80	21.76	6.45	164.87	14.18	-18.70	23.47
2-Nov-94	18.08	-9.18	22.02	6.44	164.91	14.59	-18.87	23.85
2-Nov-94	18.25	-10.68	21.82	6.33	166.78	15.39	-18.80	24.30
2-Nov-94	18.42	-9.52	19.44	5.80	165.80	14.00	-16.51	21.65
2-Nov-94	18.58	-10.45	19.95	5.79	169.54	13.90	-17.72	22.52
2-Nov-94	18.75	-10.41	20.35	5.68	169.56	13.93	-18.12	22.86
2-Nov-94	18.92	-10.30	17.75	5.56	172.36	12.57	-16.23	20.53
2-Nov-94	19.08	-8.08	17.26	4.93	172.21	10.34	-16.01	19.06
2-Nov-94	19.25	-9.33	16.72	4.93	172.28	11.49	-15.31	19.14
2-Nov-94	19.42	-9.03	15.09	4.92	172.34	10.96	-13.75	17.58
2-Nov-94	19.58	-10.62	16.00	4.60	173.21	12.44	-14.63	19.20

15m Fishing Vessel

Day 1994	UTC hour	Crosswind	Downwind	Windsp10m	WindDirT	Lee East	Lee North	LeeSpeed
2-Nov-94	19.75	-8.53	15.32	4.71	169.65	11.14	-13.53	17.53
2-Nov-94	19.92	-7.30	15.33	4.60	168.77	10.15	-13.62	16.98
2-Nov-94	20.08	-7.45	14.72	4.49	171.55	9.53	-13.47	16.50
3-Nov-94	16.25	-2.49	23.35	6.26	227.78	-15.62	-17.54	23.48
3-Nov-94	16.42	-0.89	27.75	6.79	228.88	-20.32	-18.92	27.77
3-Nov-94	16.58	-5.57	29.34	6.60	225.07	-16.84	-24.66	29.86
3-Nov-94	16.75	-8.69	29.03	6.39	230.81	-17.01	-25.07	30.30
3-Nov-94	16.92	-4.83	29.32	6.61	231.85	-20.08	-21.91	29.72
3-Nov-94	17.08	-4.06	30.21	7.03	231.96	-21.29	-21.81	30.48
3-Nov-94	17.25	-7.03	28.03	6.84	231.01	-17.37	-23.10	28.90
3-Nov-94	17.42	-4.19	27.11	6.43	229.10	-17.75	-20.92	27.44
3-Nov-94	17.58	-5.47	28.90	6.33	231.03	-19.03	-22.43	29.42
3-Nov-94	17.75	-6.92	28.99	6.56	226.38	-16.21	-25.01	29.80
3-Nov-94	17.92	-8.48	28.28	6.35	232.06	-17.09	-24.08	29.53
3-Nov-94	18.08	-6.49	25.75	6.16	229.26	-15.28	-21.72	26.55
3-Nov-94	18.25	-6.49	29.29	6.36	234.97	-20.26	-22.13	30.00
3-Nov-94	18.42	-5.96	26.65	6.27	234.99	-18.41	-20.17	27.31
3-Nov-94	18.58	-2.95	26.89	6.39	233.18	-19.76	-18.48	27.05
3-Nov-94	18.75	-9.26	25.60	6.40	236.02	-16.06	-21.99	27.22
3-Nov-94	18.92	-7.60	27.10	6.30	235.11	-17.88	-21.73	28.15
3-Nov-94	19.08	-6.79	27.18	6.40	244.50	-21.61	-17.83	28.02
3-Nov-94	19.25	-6.71	26.09	6.53	238.95	-18.89	-19.21	26.94
3-Nov-94	19.42	-7.81	27.96	6.54	238.98	-19.94	-21.10	29.03
3-Nov-94	19.58	-7.45	27.79	6.34	238.98	-19.97	-20.70	28.77
3-Nov-94	19.75	-8.26	24.82	6.45	239.03	-17.03	-19.86	26.16
3-Nov-94	19.92	-9.22	29.05	6.88	241.91	-21.29	-21.81	30.48
3-Nov-94	20.08	-6.55	26.84	6.47	244.65	-21.45	-17.41	27.63